Principles of Fire Behavior

SECOND EDITION

James G. Quintiere

CRC Press
Taylor & Francis Group

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To the memory of Philip H. Thomas, a friend, a mentor, and the father of fire science. He developed the science for many aspects of fire before others. He set the path.

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Preface

The genesis of this book is early short courses given to fire investigators of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) starting in 1992 at the University of Maryland, College Park. The material grew into a book by Delmar Publishers in 1997 within their series on fire and rescue books. The book received wide usage among institutions for the education of firefighters in the United States. Internationally, that use continued with a Korean translation in 2004 and a Japanese translation in 2009. The book was maintained as the basis in fire investigation training courses offered by the ATF for both federal and state investigators.

In early 2012, a new edition was submitted to Cengage (formerly Delmar), and it received positive reviews. Unfortunately, in July of that year, financial matters caused Cengage to terminate their fire series and this book. Now out of print, the book languished until 2015 when a fresh revision was prepared for Taylor & Francis Group/CRC Press.

The new edition aims to improve the introduction of science and math to the student. An Appendix has been added to introduce or review principles of algebra and to explain the need for mathematics in science. The book has been significantly expanded with new information and improved explanations. More examples are presented in each chapter with many related to real-world incidents. New figures and graphical results have been added, and the use of color in some should be a significant enhancement.

The student will gain knowledge of fire behavior through scientific principles and will achieve the means to make quantitative estimates for aspects of fire. The book is intended for those with a secondary education and is *not* a fundamental book for scientists and engineers. Introductions to the subjects of combustion, chemistry, heat transfer, and fluid mechanics will allow the student to learn what constitutes fire and its effects. The style of presentation is to offer simple explanations for component fire processes and to demonstrate the use of formulas to make estimations. The formulas are based on sound developments from fire research and can be tested potentially in classroom or field demonstrations. Carefully planned experiments can make much of the material in this book resonate with the students.

The book covers all aspects of fire behavior. Fire is combustion, and the student is introduced to premixed flames, the basis of ignition and explosions, diffusion flames that personify accidental fire, and smoldering, which slows down potentially deadly process. The rudiments of heat transfer are introduced with simple presentations for conduction, convection, and radiation. The concept of *heat flux* is introduced as that effect of fire that causes harm, damage, and ignition. Buoyant fluid flow caused by fire is explained in terms of the chimney and then related to flows in rooms and buildings. Fire growth

involves the trifecta of ignition, flame spread, and continued burning. Each of these elements is explained in terms of simple ideas and with information on practical data and results. The student will learn how combustion products are generated in fire, why they can do harm, and how lack of air will affect the results. Flame dynamics are explained in the open and in compartments. The stages of fire development in a room are explained in terms of flashover and ventilation-limited fires. In all cases, aspects of these subjects are given in simple but sound mathematical formulas that allow estimations. The student will learn the elements of fire and how to express them in quantitative values in the same way measurements are used to describe how to build a house. The final chapter discusses case studies related to performance-based fire safety design and to real fire investigation cases. The material in the book aims to illustrate the aspects of these cases. Application and agreement with hypothesis may not establish truth, but the examples are given to illustrate an approach.

This book is intended for several audiences. It has been used in curriculum for students in firefighting to learn the behavior of fire. Although some have found the mathematics a distraction to learning, hopefully this new edition will ease or eliminate that effect. It is essential that firefighters adopt science to guide their practices. Short courses to fire investigators have given them an additional set of tools to defend their conclusions. In addition, the use of science and its education can support their credentials in expert testimony. While the book is intended for nonengineers, I have been told that the first edition has proved a ready reference for practicing fire protection engineers and to new engineers to the field. Hopefully, the second edition will be of added benefit. Finally, the average person can learn about fire using this book. Indeed, Professor Marino diMarzo has taught "Why Do Things Burn?" an honors seminar class for nonengineers at the University of Maryland College Park since 2010, using this book. That course is a mix of lectures and hands-on student experiments to reinforce learning. It cannot be emphasized more strongly that supportive experiments for the material in this book, safely conducted, can enhance and enliven the learning process.

Acknowledgments

Before the second edition was aborted at Cengage, reviewers had sent me their comments. The unfinished form of the manuscript put an extra burden on their task with corrupted text due to a poor conversion from the original. Their positive comments and constructive suggestions gave me encouragement to complete the final second edition. I am very grateful for their input and have tried to meet their suggestions. The reviewers include the following:

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Acronyms

AIT	Autoignition temperature
ASTM	American Society of Testing and Materials
BATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
BTU	British thermal unit
CDT	Central Daylight Time
CFD	Computational fluid dynamics
FLETC	Federal Law Enforcement Training Center
FLIR	Forward-looking infrared
GDP	Gross domestic product
LFL	Lower flammable limit
NBS	National Bureau of Standards
NFPA	National Fire Protection Association
NIST	National Institute for Standards and Technology
PMMA	Polymethyl methacrylate
PRC	Product Research Committee
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
RH	Relative humidity
RMV	Respiration minute volume
SI	International System of Units
UFL	Upper flammable limit

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Nomenclature

a	Constant associated with t-squared fires, $\dot{Q} = at^2$
A	Area
$A_{F,b}$	Area of fuel covered by the flame
AIT	Autoignition temperature
$A_o\sqrt{H_o}$	Ventilation factor
c	Distance in radiation fraction equation
c	Specific heat
c	Speed of light
CHF	Critical heat flux, threshold heat flux for piloted ignition
d	Diameter
d	Thickness
D	Diameter
D_b	Maximum fireball diameter
D_m	Mass optical density, pertains to visibility
D_o	Optical density per unit path length
E	Energy
f	Frequency
f	Friction factor
F_{12}	View factor
Fr	Froude number, ratio of momentum to buoyant force
g	Earth's gravitational force per unit mass, 9.81 N/kg
h	Convective heat transfer coefficient
H	Height
H_L	Smoke layer height
H_N	Neutral plane height
HRP	Heat release parameter, $\Delta H_c/L$
HRR	Heat release rate, same as $\dot{Q}$
I	Intensity of light
k	Thermal conductivity
$k\rho c$	Thermal inertia
l	Length
L	Heat of gasification
L_b	Maximum height of fireball
L_f	Flame length
L_v	Visibility, distance able to see through smoke
LFL	Lower flammability limit
m	Mass
m	Mass of fuel burned
$\dot{m}$	Mass loss or burning rate
$\dot{m}''$	Mass burning flux, or burning rate per unit area

$\dot{m}_{a,\max}$	Maximum air flow rate
m_{CO}	Mass of CO
$\dot{m}_{smoke}$	Mass flow rate of smoke
$M_{species}$	Molecular weight of species
p	Pressure
q	Heat
Q	Chemical energy
$\dot{q}$	Flow rate of heat
$\dot{q}''$	Heat flux, or $\dot{q}/A$
$\dot{q}''_{ext}$	External radiant heat flux from hot surroundings
$\dot{q}''_{flame}$	Incident flame heat flux
$\dot{q}''_{rr}$	Reradiation heat flux from ignited surface
Q	Energy from combustion
$\dot{Q}$	Combustion energy release rate of fire
Q^*	Zukoski number, $Q^* = \dfrac{\dot{Q}}{\rho_a c_{pa} T_a \sqrt{gD} D^2}$
RH	Relative humidity
s	Stoichiometric air to fuel mass ratio usually for complete chemical reaction
S	Surface area
t	Time
t_b	Duration of burning
t_1	Time to reach 1 MW in t-squared fire growth
t_{ig}	Time to ignite
T	Temperature
T_a	Air temperature
T_{ig}	Ignition temperature
T_s	Surface temperature
T_∞	Air or initial temperature
TRP	Thermal response parameter, Equation 4.4
UFL	Upper flammable limit
V	Flame spread velocity
V_f	Original fuel volume in fireball equations
w	Width of the fuel
x_f	Flame height
x_p	Pyrolysis length
X_r	Fraction of chemical energy radiated from flame
$X_{species}$	Mole or volume fraction of species in mixture
$y_{species}$	Mass of species produced in combustion per mass of fuel supplied
$Y_{species}$	Mass fraction of species in mixture
z	Vertical height
α	Thermal diffusivity, $k/\rho c$
δ_f	Flame forward heat transfer length in spread

ε	Emissivity
ΔH_c	Heat of combustion
Δ	Means difference
κ	Absorption coefficient of the smoke or flame
κ_s	Light extinction coefficient, Equation 8.10
λ	Wavelength
ρ	Density
ρ_b	Bulk density
σ	Stefan–Boltzmann constant, 5.67×10^{-11} kW/m^2-K^4
ϕ	Parameter in Equation 5.6
Φ	Equivalence ratio

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1

Evolution of Fire Science

Learning Objectives

Upon completion of this chapter, you should be able to

- Describe what is fire
- Identify fire in history
- Describe the U.S. fire safety infrastructure and statistics
- Describe the history of fire research
- Describe the role of science to predict fire

1.1 Introduction

Before there was life there was fire. It has left its imprint on history in many ways. We need to understand the role fire has played in history, including prehistoric events as well. After all, fire has been around from the beginning. Creation may have begun with nuclear reactions, but fire was an essential consequence to the development of life. Even the ancients revered fire, as they imagined Prometheus stole it from Zeus and gave it to us mortals. Perhaps Zeus knew we would use it and abuse it, and so he punished Prometheus severely.

Today, fire in the form of controlled combustion is an essential ingredient of our technology. We could not easily survive without the burning of coal, gas, and oil. For these reasons, the study of combustion for useful power is driven by market forces that drive developed world economies. In contrast, the study of uncontrolled fire is motivated by clear risks to society and by societies having the means and desire to invest in such study. Consequently, we know a lot less about fire than controlled combustion. Fire events are chronicled and recorded in proportion to the damage rendered

to people and property. But the study of fire to understand and to improve humankind is limited. It is a complex area involving many disciplines, and it is a relatively primitive field compared to other technological areas. Yet, over the past 50 years, steady progress has been made in its subjects. This book is a by-product of those studies.

It is important to understand the history of fire science research to appreciate its contribution to the science. Equally important, it is essential to appreciate the forces that drive such studies. The impact on people and property due to fire from recent history and from past history is a driver for learning. This chapter will try to present some of this information. Of significance today is an increasing recognition in formal academic study that fire, as a subject discipline, is important. Today, fire is being studied at numerous universities around the world. The United States has two postgraduate university programs, while there are several in the United Kingdom, two in Sweden, several in Japan, and more than a dozen in China. In fact, the Chinese People's Armed Police Academy (university) outside of Beijing has about 7000 students with most studying fire regulations, firefighting, or fire investigation. Some of their faculty translated my advanced book on fire into Chinese:

> 詹姆士 G. 昆棣瑞著 = Fundamentals of fire phenomena/James G. Quintiere; 杜建科, 王平,.; James G. Quintiere; Jianke Du; Ping Wang; Yaping Gao Publisher: 化学工, Beijing: Hua xue gong ye chu ban she, 2010.

Indeed, the first edition of the current book has been translated into Korean and Japanese. Its interest has been primarily from the nonengineering communities related to firefighter and fire investigator education. Its purpose was to attempt to translate the research developments into digestible knowledge for these fields. It is couched in terms of descriptions of dissected aspects of fire growth. In addition, it includes formulas that allow predictive estimates for these phenomena. In short, it is designed to bring tools from research to the practitioner.

As a firefighter you need to react to fire with reason and knowledge, not just training and instinct. As a fire investigator you need to support your opinion with knowledge and analyses to within a scientific degree of certainty.

In this chapter, the reader is introduced to the subject of fire with its many features. What is it? Where does it come from? How does it impact us? How did its research evolve? How can we use that knowledge? In subsequent chapters, specific aspects of fire are addressed. What is the temperature of a flame? Why does flashover occur in a room fire? How does ventilation affect the fire? We will answer these questions and more by knowledge from research and formulas that allow quantitative estimates. When this information is pieced together, you might explain what you saw in a fire or why it occurred, or you might defend what you think happened.

Now let us start at the beginning.

1.2 What Is Fire?

To understand fire, we must have a scientific definition of fire consistent with our perceptions. In scientific terms, fire or combustion is a chemical reaction involving fuel and an oxidizer—typically, the oxygen (O_2) in the air. But this definition is insufficient, as rusting and the yellowing of old newsprint fit this definition and they are not fire. The distinction to be fire or combustion is that significant energy has to be released. Can we distinguish combustion from fire? Of course we cannot. In scientific terms, combustion and fire are synonymous. In conventional terms, we generally treat fire as distinct from combustion, in that fire is combustion that is not controlled. Firefighters attempt to control it by adding water or other agents, but the process of fire is not "designed" combustion, as in a furnace or an engine. Combustion experts who study such systems may know very little about fire, and those who deal with fire may know very little about all aspects of combustion. The uncontrolled nature of fire makes it distinct.

Fire is a chemical reaction that involves the evolution of light and energy in sufficient amounts to be perceptible. Generally, that energy will emit light. The color associated with fire might be blue from formative chemical emitters in a flame or yellow to red from light emitted by soot in a flame or smoldering char. Will there always be light in a flame (fire)? No. For instance, the burning of hydrogen (H_2) with air or oxygen produces only water vapor from its chemical reaction. Although significant energy is produced, we would not visibly see flame. But in most other chemical reactions, we would see the combustion process in terms of light emission from gases or particulates. A fire or a flame would be energetic enough to be sensed, particularly with sufficient energy to damage our skin. It may not be very big, but its chemical energy release rate (per unit volume) would be sufficient to give us a local burn injury. This is an operational definition of fire. Fire is a chemical reaction of significant energy release with damaging ability. It need not be only a flame, as a surface reaction on solid can fit this definition. It is the result of striking a match, the glow of the charcoal briquette in your grill, the conflagration of the forest, and the spontaneity to ignition of a large haystack. Fire is combustion, and combustion is a chemical reaction of significant energy release to cause damage. Operationally, sufficient damage can be assessed as harm to human tissue or irreversible damage to materials.

One last word on this chemical reaction called fire. On Earth, it typically and naturally involves hydrocarbon-based fuels: those composed of atoms of carbon (C), hydrogen (H), and perhaps some oxygen (O) and nitrogen (N). Man-made materials have been added to this array of fuels (molecules), with the addition of chlorine (Cl), bromine (Br), fluorine (F), and other atoms. For example, wood molecules consist of the atoms involving H, C,

and O; polyvinyl chloride (a plastic) contains H, C, and O plus Cl atoms; and polyurethane (another plastic) contains H, C, and O plus N atoms. These additions to the H—C—O base complicate the nature of combustion products and their potential threat to the environment. It is likely that other elements, even without the addition of oxygen, could meet our combustion. In short, fire or combustion is simply a chemical reaction that can suddenly occur to release significant energy with a relatively high temperature.

All chemical reactions conserve mass, which means all the atoms survive. In contrast, in a nuclear reaction some atoms are converted into new atoms with some matter transformed to energy. In a chemical reaction, while atoms are maintained, molecules are not conserved. Their destruction is the essence of a chemical reaction. A chemical reaction converts the reacting molecules into new molecules (generally called products). For combustion or a fire, the formation of new molecules from the fuel and oxygen molecules gives off a distinct amount of energy. This energy comes from breaking the binding forces that held the original molecules together.

This is as close as we get in our discussion to molecular physics. From here on, our discussion of fire principally concerns what we can see and feel. Of course we rely on some measurements, but these are at the macroscopic level in contrast to the microscopic or molecular level. More importantly, we come to rely on predictive formulae, for the processes, and effects of fire. These predictive results come from macroscopic measurements and analyses, as we will see in the forthcoming chapters.

1.3 Natural Causes of Fire

Before humans encountered and generated fire, fire was present in the universe. Natural high-temperature phenomena that can cause fire are lightning and molten rock from volcanic activity. In addition, the energy release from a high-velocity impact from space can result in fire. These phenomena date back to the formation of the Earth. As organic matter developed, we could expect to have fire. Even today, these phenomena are potential causes of accidental fire, especially lightning.

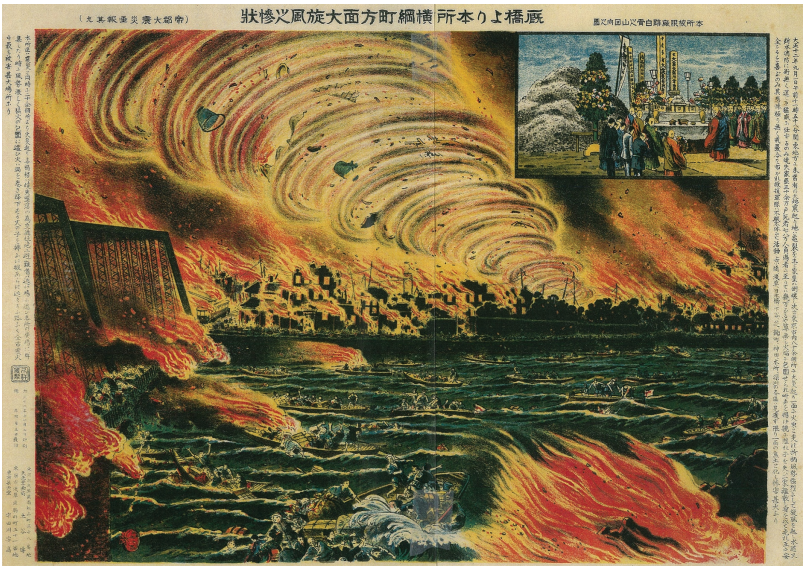
1.3.1 Lightning

Workers keeping watch over our forests record lightning strikes. These strikes can cause smoldering to the underbrush on the forest floor. A day or two after the storm, flames can erupt. The forest crews track these strikes and attempt to follow up with needed extinguishment. Lightning is even known to cause house fires. The temperatures in a lightning bolt range to several thousand of degrees, and it has enormous energy.

1.3.2 Earthquake

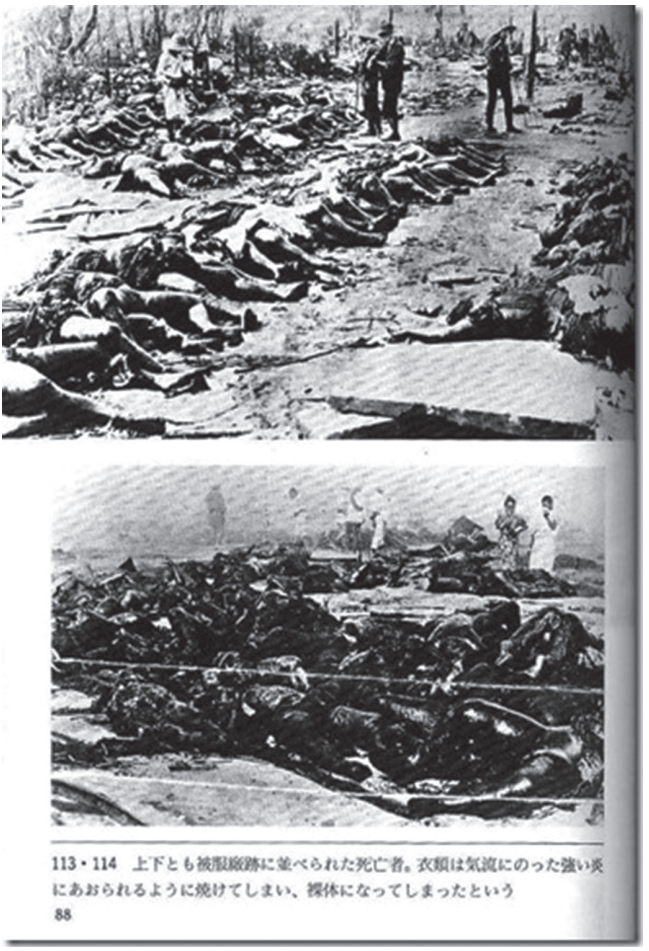
Of more concern to modern society is the effect of an earthquake. While there is no direct fire from an earthquake, the disturbance of combustion devices and fuel sources provides the means to initiate fire. An earthquake can play havoc with fire and fuel sources used for heating and cooking. Indeed, in some earthquake events, the resulting fire has caused more damage than the ground shock. This was true for the conflagrations resulting from the San Francisco earthquake of 1906 and the Great Kanto earthquake of 1923 in Tokyo and Yokohama. During the fire following the Kanto earthquake, 38,000 people were killed by a fire whirl—a flaming tornado—that spun off the main fire column. This unusual phenomenon was likely caused by winds from a nearby typhoon. People that had taken refuge in a park adjacent to the Sumida River in the Hifukusho-ato district of Tokyo were directly impacted by this large fire whirl. This horror is depicted in the Japanese print in Figure 1.1a and in the gruesome photograph of corpses resulting from the fire whirl in Figure 1.1b. A total of 143,000 people overall are reported to have perished in the Kanto earthquake and fire.

Many refer to the San Francisco earthquake of 1906 as the Great Fire of San Francisco.[1] The fire, caused by broken gas lines and disturbed gas and oil devices, burned for 74 hours after the quake. It burned over 4.7 square miles destroying 28,000 buildings. Seven hundred were reported to have died, but this could be as high as four times this number. The death toll estimate is



(a)

FIGURE 1.1
(a) Japanese painting of the Kanto earthquake fire whirl (1923) from Y. Hasemi. (*Continued*)



(b)

FIGURE 1.1 (*Continued*)
(b) Photograph of corpses killed by the fire whirl in Hifukusho-ato, Tokyo (1923) from K. Saito.

not firm, and some place it as high as 6000. Firefighting had limited water available. It was brought under control by the use of dynamiting.[1] In contrast, the Loma Prieta earthquake of 1989 in San Francisco killed 63 and caused a fire in the Marina district that destroyed four buildings. Firefighters had trouble getting water to the fire due to broken water mains.

More recently, earthquakes in Japan produced differing fire damage. Around Kobe (January 17, 1995) the Great Hanshin Earthquake, in which 6400 died, several fire conflagrations occurred. The fires destroyed over 6000 buildings. In contrast, in March 2011, the Tohoku earthquake and tsunami did not result in significant fires. However, the effects of the event on the

Fukushima nuclear facility caused explosions in three reactors. These were explosions due to the release of hydrogen gas from chemical reaction between zirconium and steam when the nuclear reactor cooling system failed. The reaction between hydrogen and air caused the explosion, as this sudden energy release failed the containment vessel of the reactor. Undoubtedly, fires in the contents resulted as a consequence. Also, the release into the atmosphere of radioactive products occurred. This dispersion of radioactive debris is a long-term hazard.

It is surprising that more study is not done on the effects of fire due to earthquake as opposed to just the structural impact of the jolt. And perhaps the consequences of fire in a nuclear facility should be studied more. The event at Three Mile Island was similar to Fukushima without an earthquake cause. That event was caused by loss of coolant to the reactor and then a similar release of hydrogen. A fire in a nuclear waste facility is another potential disaster, as airborne radioactive waste can be transported very far by the fire plume in such an accident.

1.3.3 Meteors

There is one more natural cause of fire that humankind has not experienced, but unfortunately, the dinosaurs did. It has been generally established that in about 65 million BC a large meteorite smashed into the Earth. The meteorite's passage through the atmosphere and its impact (equaling many nuclear bombs) caused frictional heating and pressure that propelled debris and fire products into the atmosphere. This resulted in a soot cloud that circled the Earth and affected the atmosphere for at least a year, causing a perpetual winter and the demise of the dinosaurs by virtually eliminating their food supply. This cataclysmic event probably occurred more than once over eons, sealing the fate of the dinosaurs and other creatures and plants. The consequences of this particular fire event are known because remnants of the meteorite (iridium) have been found in various parts of the world in the strata of rock from the same geologic time: between the Cretaceous and Tertiary periods.

The impact scenario causes smoke and dust to enter the atmosphere, block sunlight, and lower the temperature. The so-called nuclear winter has the potential to destroy much life on Earth, just as a perpetual winter destroyed the dinosaurs. This winter effect of a large fire was publicized in the 1980s when nuclear warfare studies determined that the fire from a limited nuclear war could produce debris and smoke that would result in a nuclear winter. Our world would be in jeopardy from a sustained reduction of light and temperature. Many studies were done to substantiate this "fallout" from even a survivable nuclear war. The noted science writer, Carl Sagan, was one of the strongest advocates for studying the consequences of nuclear winter. Even before the cold war ended, all nuclear parties were chilled by this possibility.

The recent meteor strike in Russian (2013) was unexpected and caused much damage from the pressure of its associated shock wave. No fires were reported as a consequence, but the event has heightened humankind's alertness to such vulnerabilities.

1.3.4 Volcanoes

Similar to the meteorite consequences, large volcanic activity has been known to cause catastrophic extinction of the Earth's species. It might be of interest to those in the United States to realize that the large crater in Yellowstone National Park is the remnant of a large volcano. It last catastrophically erupted about 640,000 years ago, launching 1,000 km^3 of rock and dust into the atmosphere. Its violent explosion would have produced tremendous damage for many miles around. In modern times, Krakatoa (May 1883) erupted with such an effect that barographs recorded it around the world. The ash was driven 50 miles into the sky, and it settled around the globe. A subsequent drop in average global temperature of 1.2°C was found. We, as those in Pompeii (AD 79) buried under 20 ft of ash and rock, are still vulnerable. This was highlighted when a volcano in Iceland erupted in 2010. Its ash cloud closed air travel over much of Europe for about a week.

1.3.5 Underground Fires

There are everyday common examples of fires in subway systems, tunnels, and mines. In addition, fire can begin and be sustained within the soil. Consider a couple of examples with historical significance.

Long after the dinosaurs, humankind evolved and eventually cultivated fire. Aristotle thought it is sufficiently important to classify it as one of the four elements of matter: fire, earth, air, and water. Fire was used and abused in many ways. Hazel Rossotti vividly describes the uses, hazards, and spiritual qualities of fire as used by society.[2] She describes how Cherokee Indians learned to preserve fire by burying a smoldering log, then digging it up, and fanning it into flames. Buried fire is now associated with waste dumps of wood or recycled plastics. Such fires can start from spontaneous ignition leading to smoldering and then flames. This process probably came as a surprise to those who experienced the Stump Dump Fire near Baltimore, Maryland in 1990. This incident involved more than 5 acres of buried tree stumps. After many attempts at extinguishment failed, the stumps were more completely buried, probably slowing the smoldering, but not extinguishing it.

A mystery in an underground fire is associated with the Terracotta Warriors found outside of Xian in China. The tombs were constructed by the first Emperor Qin about 221 BC. These tombs contain an army of life-size terracotta soldiers. On their discovery in 1974, the archaeological findings

displayed evidence of extensive fire debris at the roof level. The tombs were buried in the ground with a timber roof about 3 m below the surface. As these were secret, and completely buried, it is not known how the fires occurred. The determination of the cause—desecration, accidental in robbery, or natural—can illuminate history.[3] Fire forensics can be a tool for archaeologists that can reveal more than the artifacts themselves.

1.4 Fire and War

The use of fire in war is well known. But before World War II, fire was somewhat limited to ground operations. Aircraft bombing added to its extent and intensity. The introduction of napalm—a gelled petroleum product—added to the consequences of aerial bombing. The first systematic and sustained bombing of a city was the London Blitz lasting from about August 1940 until the Nazis invaded Russia in June 1941. Incendiary bombing was not used. But by 1943, the Allies established a policy to disturb life in large cities by destroying large areas of the city and halting normal life activities. This was designed to target the morale of the population.[4]

The first city targeted with this policy intention was Dresden. It was bombed on February 13, 1943 at 10:13 p.m.[5] Four thousand pound bombs were used to splinter the structures to make them more combustible. Incendiary napalm bombs followed this first attack. The fires were seen from over 100 miles away. A storm arose; as far as the eye could see, this was given the name, *firestorm*. Survivors said it was like being in a burning stove. Currents of air and fire bombarded the fleeing people. Those that could not move were asphyxiated where they stopped. Over 75,000 apartment buildings were destroyed, and likely 40,000 died, but this number is debated.[5]

The next firestorm occurred in Hamburg on March 27/28, 1943.[4] Lancaster and B-17 bombers were prominent among nearly 800 aircraft. "The whole yard, the canal, in fact as far as we could see, was just a whole, great, massive sea of fire."[4] Six thousand apartment-block buildings burned in a 1.5 × 3 mile area. People were ignited by the radiation, some were blown into burning buildings, clothes were torn off, air was sucked out of shelters, and 40,000 likely died. The massive fire caused hurricane force winds at ground level, broke branches, and even uprooted trees. The fire raged for 5 hours.

These large-area fires suck in air from all directions. They pull the oxygen out of the core and bring high-speed air around the perimeter and into the center. This is the firestorm. Its name was invented at these fires.

The term *firestorm* was never applied to incidents in Japan. But General Curtis LeMay used the same tactics in bombing Japanese cities. These tactics were refined and studied during bombing experiments in the summer of

1943 at Dugway Proving Grounds in Utah on a simulated city known as "Little Tokyo." They demonstrated the vulnerability of the traditional Japanese wooden houses. During the spring and summer of 1944, most major Japanese cities were carpet bombed by B-29 bombers. Of these major cities, from about 25% to 75% of the city's areas were obliterated and turned to ash. In Osaka, 16 miles^2 were destroyed in contrast to 3 miles^2 destroyed in the Great Chicago Fire of 1871.[6] This destruction far exceeded the effects of the atomic bombs on Hiroshima and Nagasaki.

There is no doubt that henceforth fire will be part of war. Yet with a smaller "weapon," a single aircraft filled with liquid fuel was the instrument of destruction for World Trade Center Towers and the Pentagon. Those were aircraft fuel–initiated fires that ultimately led to sustained fire spread over ordinary contents and heat-induced failure of the structures. The cause of the fires is clear, but the reason for the destruction of these fire-resistive buildings is not so evident.

1.5 Fire in the United States and Abroad

History is punctuated with fire disasters. The Great Fire of London (1666) and the Chicago Fire (1871) caused the destruction of thousands of buildings. These were literally forest fire–like events in that wind was a principal factor in their spread. Once the wind died, the fire stopped. Mechanical suppression apparatus could not deal with such fires until calm conditions prevailed. These fires were conflagrations or mass fires involving large tracts at a given time. Their lateral flame extent is much greater than their flame height. It was noted that similar large fires resulted in World War II from such bombing raids as Hamburg, Dresden, and Tokyo. Today, we begin to see some return to large conflagrations of dwellings as urban development has spread into the forest. The term *urban wildland* fire has now been coined to refer to these fires.

1.5.1 U.S. Statistics

It is instructive to put the catastrophes of fire into perspective against other natural and technological disasters. Indeed, many of the greatest disasters in recent history from natural phenomena are likely to be due to fire. Table 1.1 lists the top 25 U.S. disasters by death toll. The fatality level ranges from 400 to possibly as high as 12,000. More than 40% involved fire. So, fire is a major contributor to large life loss catastrophes.

Such enormous disasters are relatively infrequent as they span over more than 100 years. Instead, it is the local effects of fire that have contributed to our perception of its hazard. According to National Fire Protection

TABLE 1.1

Top 25 Disasters in the United States by Death Toll (Excluding Epidemics and Heat Waves)

Event	Date	Fatalities
1. Hurricane, Galveston, TX	1900	6,000–12,000
2. Earthquake and fire, San Francisco	1906	450–6,000
3. Hurricane, Great Okeechobee, FL	1928	1,800–3,000
4. 9/11 Terrorist attacks	2001	3,000
5. Military attack, Pearl Harbor, HI	1941	2,500
6. Flood, Johnstown, PA	1889	2,200–3,000
7. Hurricane, LA	1893	2,000
8. Hurricane Katrina, LA, MS, FL, AL	2005	1,830
9. Ship explosion, Sultana, Mississippi River, TN	1865	1,500–1,700
10. Peshtigo fire, WS, MI	1871	1,200–2,500
11. Ship fire and sinking, East River, NYC	1904	1,000
12. Hurricane, Sea Islands, SC, GA	1893	1,000–2,000
13. Ship sinking, S. S. Eastland, Chicago	1915	800
14. Tri-State Tornadoes, MO, IL, IN	1925	700
15. Fire, Iroquois Theater, Chicago	1903	600
16. Hurricane, Florida Keys	1919	600
17. Flood, St. Francis Dam, CA	1928	600
18. Hurricane, New England	1938	600
19. Explosion (ship), Texas City, TX	1947	550
20. Wildfire, MN	1918	500–800
21. Wildfire, MI	1871	500
22. Fire, Cocoanut Grove, Boston	1942	492
23. Tornadoes, Tupelo (MS)–Gainesville (GA)	1936	430
24. Floods, OH	1913	430
25. Hurricane, Labor Day, FL	1935	400

Note: From various sources with estimated death tolls.

Association (NFPA) over 1.3 million fires were reported in the United States in 2010, with about 480,000 in structures, 200,000 in vehicles, and 630,000 outside.[7] With a U.S. population of 308 million, this suggests a structural fire each year for at least 1 in 200 households. This is the frequency of fire occurring possibly in your home. Roughly 3700 civilian deaths occurred in 2010 in the United States. For a total population of 308 million with a life expectancy of 70 years, we calculate

$$\frac{308 \times 10^6 \text{ people}}{70 \text{ years} \times 3100 \text{ deaths/year}}$$

or roughly 1 in 1400 people will die by fire in the United States over your lifetime. This fire fatality frequency is roughly 10 times more than for automotive deaths. As an alternative check on these rough estimates, the National Safety Council estimated for 2007 that the chance of dying by fire in your lifetime is 1 in 1177, while dying in a motor vehicle is 1 in 88.

So with these current frequency estimates, you may have a neighborhood fire (over roughly 200 households) about once a year, and you may know at least one person who will die by fire during your lifetime. These fire statistics relative to other threats to people and property do not cry out for a great concern about fire.

The causes of fire in dwellings for the United States are displayed in Figure 1.2. The major causes are cooking and heating equipment. These are technological causes, except for the human role in cooking fires, and they extend to areas of electrical appliances, lighting, and clothes washing and drying appliances. Intentional is still significant, and could even be higher, as this is not an easy call.

The U.S. overall death rate due to all accidents since about 1900–2010 has steadily dropped from about 80 per 100,000 of population to 40.[8] Figure 1.3 shows the relative significance of fire with other accidental causes of death in 2009. It clearly shows that fire plays a small role compared to other accidental causes.

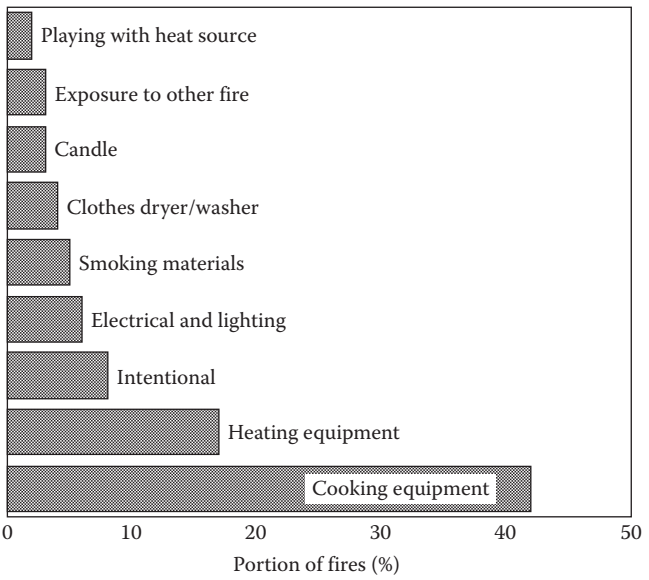


FIGURE 1.2
Causes of fire in homes in the United States 2005–2009. (From *Accident Facts*, National Safety Council, Itasca, IL, 1995.)

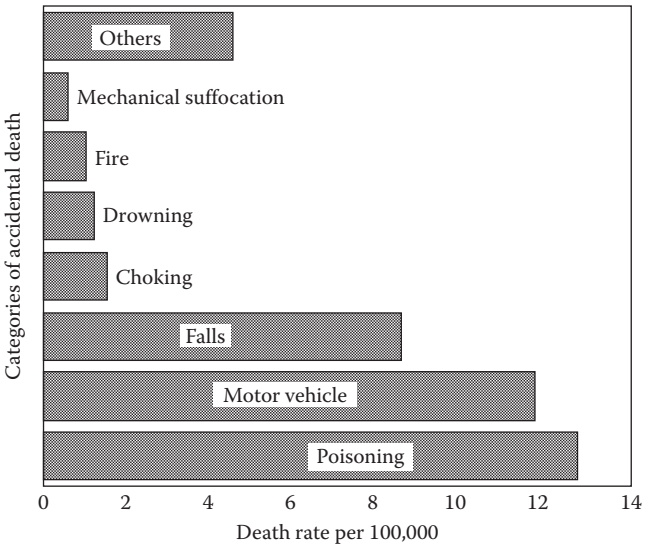


FIGURE 1.3
Death rate due to unintentional injuries 2009. (From *Accident Facts*, National Safety Council, Itasca, IL, 1995.)

1.5.2 United States and the World

It is of interest and curiosity to compare the U.S. fire statistics with the rest of the world. The Geneva Association (www.genevaassociation.org) maintains a program that tracks these statistics, and some additional country data came from Brushinsky.[9,10] In Table 1.2, the death rate statistics are given as produced in the first edition and amended to more recent times. China is updated to 2004.[11] It is difficult to draw generalities from the data, but there are some trends.

Cold weather countries tend to have generally high death rate from fire. China and Russia are at opposite ends, and one might wonder about these data. Statistical data for South America, the Mid-East, and Africa are not generally available. It is a benefit to have these statistics, as they can set policy for a country. Also, if we learn what underlies the statistics in one country, we might benefit others. Social, culture, technology, climate, and prevention measures all play a role in these statistics.

1.5.3 U.S. Fire Prevention Infrastructure

Fire events and statistics do move people to action. Throughout the twentieth century, much effort has been put into the prevention and protection from fire. In the United States, following the Great Fire of Baltimore (1904) and the fact that the property loss due to fire was then 10 times that of Europe, a national research program was initiated at the National Bureau of Standards (NBS)

TABLE 1.2

Annual Fire Deaths per 10^5 Persons

Country	1992–1994	2004–2008	Country	1992–1994	2004–2008
Russia	10.6[a]	—	France	1.26	0.98
Hungary	3.31	1.81	Czech Republic	1.21	1.41
India	2.20[a]	—	Germany	1.17	0.68
Finland	2.18	2.08	Australia	0.93	0.48
Union So. Africa	2.00[a]	—	New Zealand	0.92	0.75
United States	1.95	1.21	Spain	0.86	0.58
Denmark	1.64	1.28	Poland	0.80[a]	1.56
Norway	1.60	1.33	Austria	0.74	0.46
Canada	1.58	1.15	Netherlands	0.63	0.52
Japan	1.52	1.62	Switzerland	0.53	0.30
United Kingdom	1.49	0.80	Italy	0.30[a]	0.46
Belgium	1.47	1.21	China	0.20[a]	0.19[b]
Sweden	1.35	1.20	Singapore	—	0.11

Source: *World Fire Statistics Centre Bulletin 12 & 27*, The Geneva Association, Geneva, Switzerland, 1996/2011 for 1989–1992.

[a] From Brushlinsky et al.[9] for 1994.

[b] From Guo and Fu.[11]

to investigate the consequences of fire on building construction materials. Steel and concrete buildings were not necessarily found to be "fireproof." The NBS fire program in 1913 was established under Simon H. Ingberg who would head the Fire Resistance Section of the Heat Division for the next 40 years. In 1914, due to a Congressional mandate, funding and the challenge of the complex fire problem inspired much work at NBS. NBS history states "so broad became the scope of the investigation that it soon involved almost every one of the scientific and engineering laboratories of the Bureau."[12]

In addition, the National Fire Protection Association (NFPA) was established in 1896 to provide a voluntary basis for technical information and standards—recommended procedures and practices—concerning fire safety. In addition, in those early years, the Underwriters' Laboratory and the American Society of Testing and Materials began to contribute standard test methods to assess performance in fire conditions. This led to fire resistance tests that enable the measurement of the endurance of structural elements of buildings and structures in fire. Such tests, conducted in standard furnaces throughout the industrialized world, help to ensure that structures do not collapse because of fire. But all fires do not match the conditions of the standard fire resistance furnace tests, and practices are not universal in their attempts to match the testing results to actual anticipated fire conditions. More striking is the fact that "standard" furnaces do not always impart the same fire heating conditions. Standard practices are not universal throughout the world, and their application to real fire conditions is far from perfect.

1.5.4 Motivation for Improvement

In the early 1970s, it was acknowledged that the United States had the highest annual death rate from fire of the world's industrialized nations. It had fire deaths per year listed at 12,000. Once research commenced, this was quickly reduced when it was found that an error in compiling vehicle fire deaths had been listed as 4000 instead of 400!

Congress passed the Fire Prevention and Control Act of 1974. This act structured the U.S. Fire Administration to enhance the practice of firefighting, to improve education, to assess national fire statistics, and to develop research. It focused research on the development of fire in buildings: ignition, flame spread, smoke, and *flashover* (a sudden event in fire growth that rapidly leads to full involvement of a room). The safety of people rather than structures became the focus. This attitude of mandated public safety, coupled with the threat of civil suits due to issues affecting fire safety, motivated the increasing use of innovative fire safety technologies. These included residential smoke detectors, smoke control systems in large buildings, and the extension of sprinklers to public and residential occupancies. Indeed, many of these technologies have attributed the drop in annual U.S. fire deaths by more than half of the 8000 in the early 1970s. Most of this drop is attributed to the widespread use of smoke detectors. This is remarkable.

Changing technologies bring improvements in fire safety but can also bring new risks. The high death rate due to fire in the United States and in other industrialized nations may be associated with the changing technologies with which we live. Change brings risks, some unexpected. For example, in the 1970s, lightweight cellular plastics (such as foam polyurethane and polystyrene) were seeing new innovative applications, but their fire hazards were not fully appreciated. Standard tests suggested no problems, but accident scenarios showed a dramatically fast rate of fire spread. These incidents brought standard flammability tests into question. The Federal Trade Commission (FTC) enjoined the plastic industry to take corrective action. The Product Research Committee (PRC) was established by industry in 1974 to examine this issue for cellular plastics as a result of a consent order between the FTC and the industry.[13]

1.5.5 Flammability Tests

Although the PRC group gained much insight into the issue of foam plastic flammability, it remains unresolved today. To mitigate concern, today lightweight cellular plastics are generally required to be covered by wallboard in building construction applications even after they pass the test requirements for flammability. Confidence in their flammability ratings by standard tests is low. But this issue of product flammability is not unique to cellular plastics; it is widespread.

The disparity among flammability tests for construction materials is illustrated in Figure 1.4 for six national European tests in the ranking of 24 materials. Professor Howard Emmons publicized this chart after he discovered these data in Europe during a world tour to review the status of fire science.[14] Perfect correlation among all of the six tests should produce the same ranking for the 24 materials; this would be a 45° straight-line correlation. For example, the number 6 material should be ranked as 6 by all the tests for a perfect correlation of flammability. The tests decidedly do not correlate! Each country's test gives a different measure of flammability for the same material.

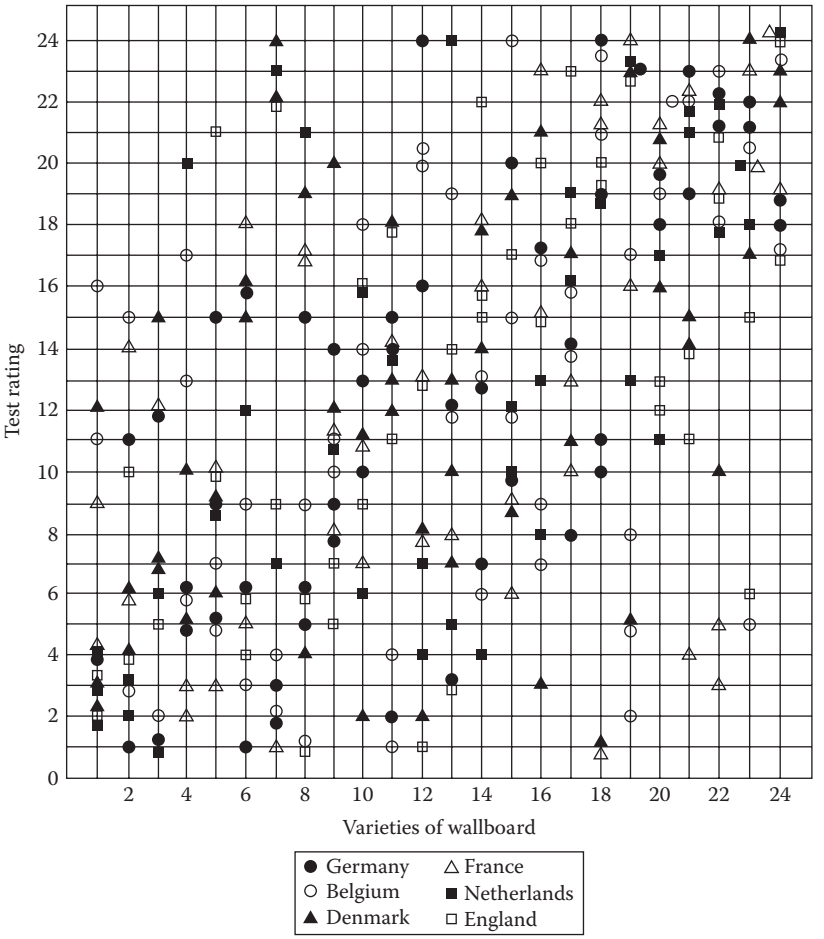


FIGURE 1.4
Disparities among fire tests—rankings of 24 materials by six national flammability test methods. (From Emmons, H.W., *Fire Res. Abstr. Rev.*, 10(2), 133, 1968.)

The results are not consistent, giving ambiguity to the term *flammability*. Perhaps it is appropriate that in a book intended to present accurate prose, the word flammable is listed among those misused:

> *Flammable*, an oddity, chiefly useful in saving lives. The common word meaning "combustible" is inflammable. But some people are thrown off by the in- and think inflammable means "not combustible." For this reason, trucks carrying gasoline or explosives are now marked flammable. Unless you are operating such a truck and hence are concerned with the safety of children and illiterates, use inflammable.[15]

This change in the word was likely done in the interest of safety, but it can still cause confusion, especially if you are French. A clear scientific basis is needed to classify the fire hazard of materials.

We still do not currently have a universal test procedure to establish flammability or, alternatively, inflammability. These current tests are reflections of our misuse of the word. The world cannot seem to establish a universal test. In the 1990s, Europe sought to harmonize its flammability tests. First, they considered the tests of the "Three Sisters": national tests of Germany, France, and the United Kingdom. The results gave a chart again like the Emmons graph. They were using as a benchmark the Room Corner Test. That test measures the energy release of fire spreading on a wall and ceiling material in a room subject to a corner ignition. That is a realistic test for lining materials, but it is expensive. So, the desire is instead to have a small laboratory inexpensive test as the standard. They focused on the Cone Calorimeter as a candidate test for the standard. That test can measure the time to ignition and the rate of energy released by a material. This seems like a good scientific match. But fire standards are political, between the pride of countries, and the impact on commercial products. Some plastic materials did not look good in the Cone test, and ultimately, a new test was invented to "bring harmony" to Europe. This should not be the way progress is made for fire safety. If only industry and countries would realize that a universal test based on scientific measurements can be a blessing. A blessing is not just to safety but also to the cost of doing business and streamlining commerce. Even if it is not at first a perfect test, a scientific test can be built upon with future knowledge and made better. Today, an ad hoc test with defects is commonly replaced by another arbitrary test.

1.5.6 Cost of Fire

The annual costs of fire are not insignificant, but because of the relatively low frequency of fire compared to other societal threats, they are not fully appreciated. Moreover, fire safety costs do not increase the productivity of the economy; they are a drag on the economy. Costs have to be expended to make buildings safe from fire and to make products

less likely to contribute to fire. When these costs become too great, more attention will be made to minimizing them. For now they are viewed as regulatory costs that are a necessary burden to business. The cost of fire safety is a societal issue.

It was estimated in 1991 that the annual cost of fire in the United States was $85 billion.[16] The overall cost includes property loss, business interruption, product liability, insurance administrative costs, fire service (paid), and fire protection in construction and equipment. Today, this cost is much higher. Table 1.3 shows the percentage of major country fire costs scaled to their gross domestic products (GDP) for 2002–2008.[9] The costs for the United States (2008) in actual dollars are as follows: property loss $17 billion, fire protection in construction $62 billion, fire service $41 billion, and insurance administrative costs $18 billion for a total of $138 billion.[9] The cost continues to increase, likely due to inflation.

But as can be seen, it is typical for many developed countries to invest nearly 1% of their GDP in fire-related costs. The United States appears to spend the most relative to GDP. Unfortunately, not even 1% or 2% of these fire costs are invested back into improving our knowledge of the

TABLE 1.3

National Annual Fire Costs by Percentage of GDP for 2002–2008

Country	Property Loss	Building Fire Protection	Fire Insurance Administration	Firefighting	Total
Canada	ND	0.32	ND	ND	ND
Spain	0.08	ND	ND	ND	ND
Japan	0.12	0.14	0.09	0.30	0.65
Finland	0.17	ND	0.03	0.20	ND
United States	0.11	0.41	0.12	0.27	0.91
Slovenia	0.07	0.16	0.06	0.05	0.34
New Zealand	0.11	0.23	0.08	0.16	0.58
Germany	0.13	ND	0.04	ND	ND
Netherlands	0.16	0.31	ND	0.19	ND
Australia	0.08	0.35	ND	0.16	ND
United Kingdom	0.13	0.22	0.10	0.21	0.66
Italy	0.17	0.35	0.05	ND	ND
Denmark	0.20	0.26	0.09	0.07	0.62
Sweden	0.17	0.19	0.05	0.13	0.54
France	0.20	0.18	0.07	ND	ND
Norway	0.20	0.36	0.10	0.11	0.77
Singapore	0.05	0.39	0.02	0.03	0.49

Source: *World Fire Statistics Centre Bulletin 12 & 27*, The Geneva Association, Geneva, Switzerland, 1996/2011.

ND, data not available.

technology of fire safety. For the United States, the investment in research is less than 0.04% of annual cost of fire today by my estimates. Typically, industry will invest more than 3% of its revenue into research to improve its products.

In 1975, when the most productive research period for fire research occurred in the United States, the investment was about 0.06% of total fire costs. Not a big difference, but a lot more money to stimulate research and make progress was available back then. Today, this would amount to an increase in research for fire at about $27 million per year or more. This is not a lot of money for society to invest, but it would make a big difference for fire safety. There are few advocates for such an increase. Lessons are not just learned from history but must also be analyzed using the science of fire. Research is needed to lay the foundation of the full knowledge base. Perhaps the future will bring more fire research as fire investigators and firefighters are becoming more sensitive to its potential benefits.

Doubtless, future disasters will shape the course of fire safety. In developing nations, high-rise buildings are being built to heights that dwarf current levels. It is possible that thousands of occupants will be seriously affected or killed by a fire disaster in a high-rise building. The previous sentence was in the first edition published before September 11, 2001. The WTC 9/11 fire event is now classified as the "deadliest large loss fire" in history with over 2000 dead and a loss of $41 billion (in 2010 $) according to NFPA.[7] Since then there has been the Caracas Tower fire (2004) with flames traveling from the 34th floor to 26 stories above; the 38-story Windsor Building fire in Madrid (2005) that burned for more than 24 hours; and the Beijing Mandarin Oriental Hotel (550 ft tall), unoccupied, burned out completely in 3 hours. Fortunately, loss of life was not the issue in these three buildings, but the vulnerability of tall buildings to fire is key. Fire safety in tall buildings deserves special attention.

Future living arrangements in outer space under low gravity and in underground and undersea structures will present unexpected fire hazards. Many large cities around the world are moving underground, especially for people in commuting and for shopping. We already see the issues with moving into the forest environment. Issues related to seeking new forms of power will bring new problems. Electric and hydrogen-based vehicles will present new fire issues. With hydrogen it is obvious, but higher voltage batteries will be the likely cause of fires in the new more combustible vehicles. Fire affecting radioactive operations and toxic waste storage sites will continue to present hazards of new dimensions. We have already seen this at Fukushima. There will be new fire hazard surprises in future technological advancements and products despite improvements in fire safety technologies. We are likely not to fully anticipate the fire hazard of new technologies.

1.6 Fire Research

The study of fire is a complex subject that comprises an array of interdependent disciplines. Each of these subjects needs to be developed before the pieces can be put together to adequately describe fire. Science is the evolution of many steps and contributions. Eventually, the subject takes shape, and individuals formulate or unify the subject by quantitative description that allows for predictions and assessments. This process leads to a formally recognized scientific discipline for a subject. Let us briefly examine the history of these component subjects that underlie fire.

1.6.1 Disciplines That Underlie Fire

Fire is uncontrolled combustion involving chemistry, thermodynamics, fluid mechanics, and heat transfer. Thermodynamics, the study of energy and states of matter, was principally shaped by Willard Gibbs, a noted nineteenth-century scientist, who brought unification and clarity to the subject that is still appreciated today. Heat transfer also had its roots in the early 1800s. Joseph Fourier, a general in Napoleon's army, formulated the law of heat conduction that forms the theoretical basis of the field. But heat transfer in fluids had to await the development of modern fluid mechanics in the late 1800s when the pioneering work of Osborne Reynolds on turbulent flow laid the basis for practical engineering analysis in fluid mechanics. In the 1900s, Theodore von Kármán and others advanced the subject of aerodynamics, which paved the way for a more complete framework for heat transfer. At this point, solutions were based on approximate methods, since the governing mathematical equations were too complex to be exactly solved. In combustion, Y.B. Zel'dovitch, a Russian scientist, was able to formulate solutions for diffusion flames using innovative approximate mathematical techniques. Although begun in the 1930s, the subject of combustion was not developed to a mature state until the 1950s.

1.6.2 Computer Simulations and Physics

Today, fast and large capacity computers make it possible to approximately solve the basic equations with good accuracy. Many facets of combustion can be rendered by computer simulations, but issues of turbulence, chemical kinetics, and other small-scale phenomena still cannot be completely resolved by these computer solutions.

Over the last decade, many more engineers and investigators of fire are now turning to computer solutions. The Fire Dynamics Simulator, originating from National Institute of Standards and Technology (NIST), presents a graphical user-friendly tool. The code is based on the solution of the fundamental governing equations but still must rely on underlying models

for combustion and turbulence. FMGlobal has embarked on an alternative code called FireFOAM. These efforts are advancing the state of the art in fire computation. There is no doubt that as computers get still bigger and faster, these computer simulations will be invaluable.

As with all models, computer codes can be misused, as they can present realistic graphical renditions of fire and smoke in their output. The results may *look* right but can be quantitatively inaccurate. Such results must always be validated for their specific application. This validation must rely on experimental data that bring generality to the problem. Such experimental studies have been the backbone of engineering science. They have laid the foundation of formulas that match the generality of the data and circumvent the need for fundamental mathematical solutions involving complexities of turbulence and combustion. This book deals with these backbone formulas. The use of such formulas relies on understanding the subject. The engineer must rely on intellectual insight and understanding to use these approximate formulations correctly. Only when a thorough understanding of a subject is mastered can simple representations of complex phenomena be made and appreciated. These formulae and their development form the basis of education and the transfer of knowledge. Without this basis, we can just turn on the computer and get an answer. We need both computer simulations and approximate formula for specific processes. The intelligent use of both approaches is key for design and analysis. They should provide a countercheck to each other.

1.6.3 Brief History of Fire Science

Let us return to the history of fire science. The subject of fire needed to build on all of its component disciplines. These interactions among the disciplines had to mature before it was even possible to adequately describe and predict fire. I can remember in the 1970s combustion scientists talking to behaviorists, chemists talking to toxicologists, and firefighters talking to engineers. These discussions are needed today to bring a balance to the science of fire.

Another factor influencing the development of fire science is the motivation to study it in the first place. We can see that fire is a drain on the economy, and there is no direct market incentive for its study. In Japan, the consequences of earthquakes led to an extreme sensitivity to fire safety and its study. Fire science is studied in schools of architecture in Japan as well as in other scientific fields. It is endemic in Japanese culture and academic disciplines. Not surprisingly, the first science-based handbook on the quantitative description of fire was published in Japan in the early 1980s. Even today I am amazed at the infrastructure for fire research in Japan. At their annual scientific meetings, it is not uncommon to have up to 100 technical presentations on fire. Indeed, the first Society of Fire Protection Engineers (SFPE) standard issued in May 2011 (SFPE Engineering Standard on Calculating Fire Exposures to Structures) is derived from Japanese research and standards.

In 1949, England developed one of the most advanced scientific laboratories for fire study in the world (the Fire Research Station, formerly at Borehamwood). Much of the work through the 1960s was performed under the leadership of Dennis Lawson, Philip H. Thomas, and David Rasbash. Rasbash went on to establish the first graduate program in fire engineering at the University of Edinburgh. P.H. Thomas has been a main force in disseminating the benefits of fire science throughout the world. Some have said that he was first to work on many of the subjects of fire and got them right. Their work has not been fully appreciated today because much of it was never published in mainstream fire journals. However, today the Fire Research Notes (1952–1978) can be accessed online through the International Association for Fire Safety Science (IAFSS, www.iafss.org). The IAFSS was formed in 1986 with P.H. Thomas as its first head. It was established to facilitate the transfer of fire research around the world, and its proceedings contain some of the best of fire research developed.

In the United States, extensive fire research emerged after Japan and the United Kingdom. A special meeting can mark its start. On November 9, 1959, many of the pioneers of fire science came together in Washington, DC, for "The Use of Models in Fire Research." Walter Berl, the conference organizer, commented, "The intimate interplay between aerodynamics, heat transfer, and chemical reaction rates makes the study of fires the intriguing problem it is."[17] Scientists who had achieved prominence outside the field of fire were present at this meeting and elected to study fire because of its challenge and the prospect of its benefits to society.

In the United States, one of the earliest scientists of fire was Hoyt Hottel of M.I.T. He began the study of fire before World War II but was diverted to study the effects of fire from weapons during the war. Later, he and Howard Emmons of Harvard University pursued fundamental research in fire and lobbied for government research funding. Such research support was realized in the early 1970s by expansions of fire research at the Factory Mutual Research Corporation (now FMGlobal) and at the NIST (formerly the NBS). These laboratory expansions and growth into academia were enhanced and enabled by funding for fire research from the National Science Foundation and through the National Fire Prevention and Control Act of 1974. The fruits of that U.S. research effort in the 1970s helped to promote, develop, and catalyze the disconnected efforts of fire research throughout the world. Although U.S. funding for basic research in fire has since decreased, the worldwide activity is expanding in its communication links, and there is a healthy exchange of knowledge in this small field. For example, proceedings of the symposia sponsored by the IAFSS help to maintain international exchange in fire research. These proceedings are available online at www.iafss.org. Also, the *SFPE Handbook of Fire Protection Engineering*[18] is a good illustration of the current knowledge base of fire science compiled by experts among the disciplines of fire. It is this synthesis of fire research that makes possible this current book.

1.7 Visualization of Fire Phenomena

It is crucial to have a visual concept of fire phenomena before one can establish a framework for study. Many effects are seen (or can be seen if planned) during the progression of fire and its related smoke movement. These images must be categorized into scientific terms if we are to learn. The shape of a flame is influenced by the fluid flow induced by the flame itself. The nature of smoke movement in buildings can take many forms. Such visualization must take place in a laboratory for systematic study, but firefighters and others must be able to articulate their observations to scientists to promote real study. The scientist cannot allow the size of his laboratory to limit the scope or relevance of his observations in fire phenomena. However, small-scale studies can be very relevant. We all appreciate the role of wind tunnels in the design of aircraft and in improving the aerodynamics of motor vehicles. The Wright brothers had a wind tunnel at their disposal. Such scale modeling techniques pervade many fields of study; fire is not excluded. Physical scale models based on the laws of science can help to design aircraft, ships, oceanic tidal basins, concert halls, and even analyze vehicle crash dynamics. Scale models can also reasonably represent processes in fire. Many of the formulas we will study in this book have resulted from small-scale experiments and extrapolated to larger scale by using scientific and mathematical principles. A deep understanding of the subject allows a full appreciation of the scale independence of such formulas.

Figure 1.5 is a schematic illustration of phenomena arising in a room fire. The recognition of these and other phenomena shown there helped to establish a framework for the "modeling" of compartment fires. Figures 1.6 and 1.7, respectively, show the dynamics of smoke movement and fluid flow in a corridor subjected to a room fire.[12] The results were accurately established using a scale model with glass walls and colored smoke to make the processes visible. These photographs show the classical representation of an apparent uniform smoke layer filling the upper half of a compartment (Figure 1.6) and the complex recirculating flows that occur both in the smoke layer and in the relatively clear space below (Figure 1.7). Figure 1.6 also illustrates the mixing of smoke into the lower clear space (at the right) as air enters through a window and entrains smoke.

Figure 1.8 shows fascinating flame patterns as a result of flames impinging on a ceiling.[20] The patterns depend on fuel type, fuel flow rate, and spacing to the ceiling. No computer simulation has yet to predict these flame shapes.

Today, the availability of small inexpensive video cameras makes it possible to see fire behavior in room and building fire experiments that were previously too difficult to see. You cannot model it and confirm it without solid data, and visualization is an essential key.

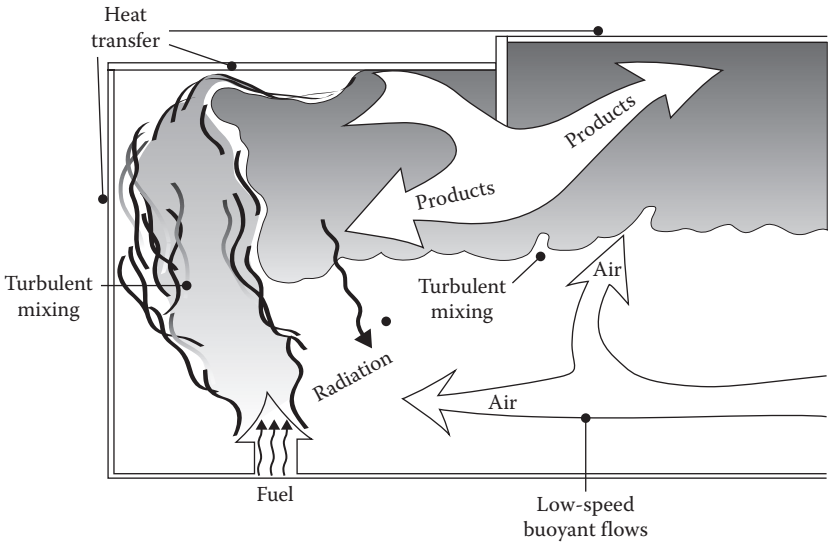


FIGURE 1.5
Phenomena in room fire growth.

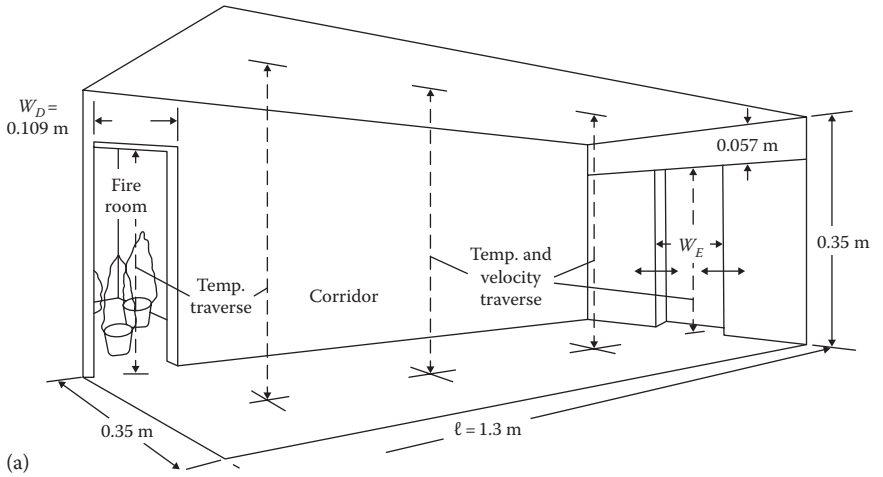


FIGURE 1.6
(a) Schematic of a scale model corridor subject to a room fire at the left (doorway width, W_D = 11 cm) and exiting through the right (through a doorway width, W_E). (From Quintiere, J.G. et al., *Fire Mater.*, 2(1), 18, 1978.) (*Continued*)

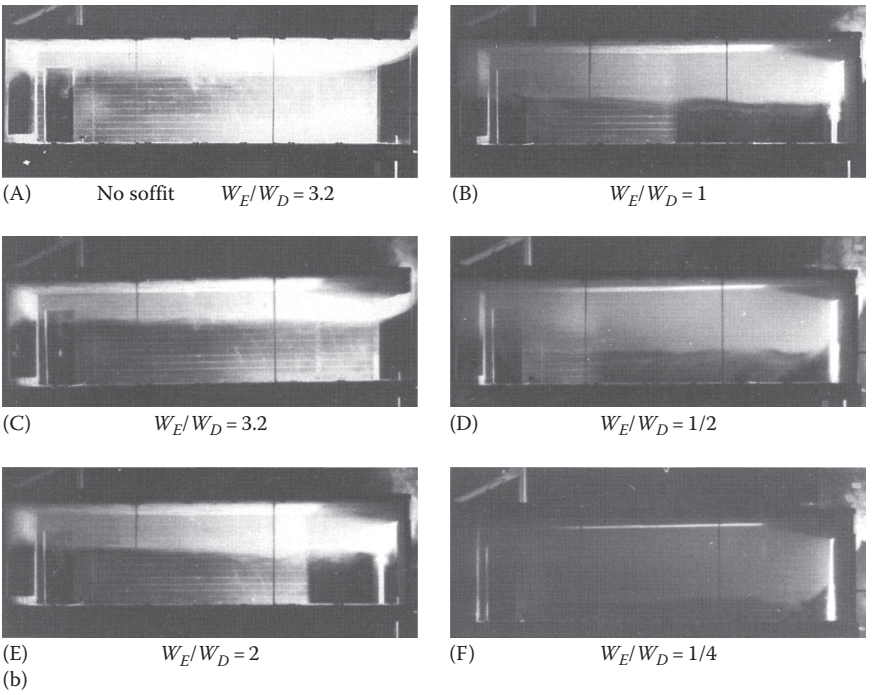


FIGURE 1.6 (*Continued*)
(b) Smoke layer in a scale model corridor subject to a room fire at the left (doorway width, W_D = 11 cm) and exiting through the right (through a doorway width, W_E). (From Quintiere, J.G. et al., *Fire Mater.*, 2(1), 18, 1978.)

1.8 Scientific Language

In order to relate concepts and principles behind fire phenomena, we must first qualitatively understand the behavior of fire. More importantly, we must understand the information and methods used to quantitatively describe specific fire phenomena. Knowledge of physics and algebra is needed. Units for measure, symbols, and scientific notation provide the language for quantitative analyses. If the reader is weak in the area of algebra and units of measure, the section in the Appendix should be read before proceeding further in this book.

1.8.1 Units of Measure

In today's world, despite the lagging of the United States in the metric system, the International System of Units (SI) is in widespread use. The scientific community has universally adopted this system in its publications. To understand articles in fire science, it is essential to be conversant with the

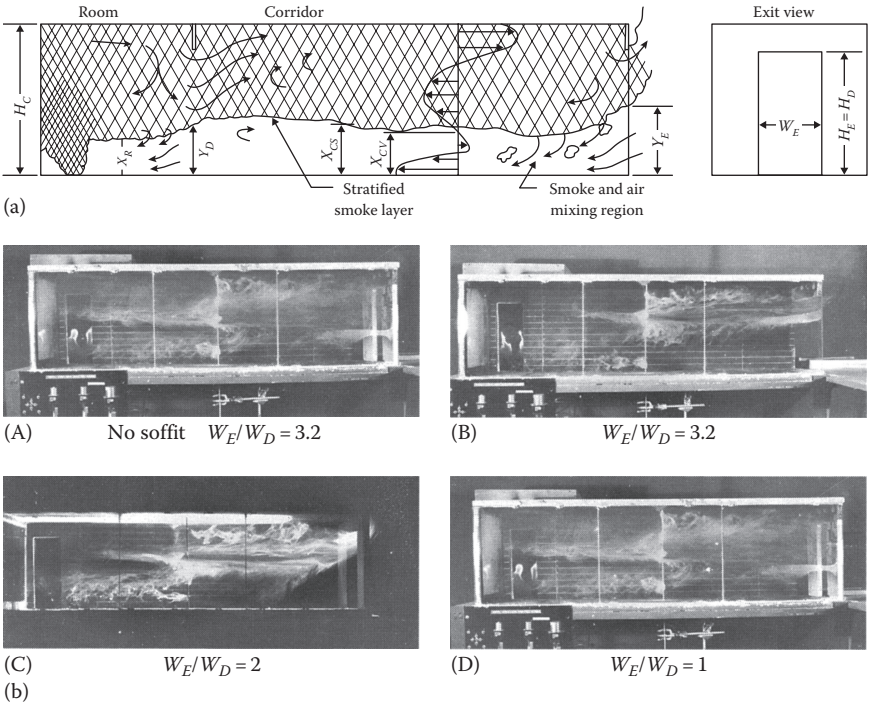


FIGURE 1.7
Smoke streaks showing the complex flow pattern in a scale model corridor subject to a room fire. (From Quintiere, J.G. et al., *Fire Mater.*, 2(1), 18, 1978.)

SI units. Table 1.4 lists the SI units for quantities relevant to the subjects in this book. The quantities listed arise from the component disciplines of fire. These quantities will be introduced as we proceed in the book to develop the scope of fire phenomena.

As an example, let us consider energy. Table 1.3 lists the unit of energy as a joule (J). The English System of units, common to the United States, would alternatively have BTU units (British Thermal Units) for energy. 1 BTU is 1055.056 J or about 1 kJ. An alias for a joule is W-s (watt-second). It is common to name units after scientists from the field and to present aliases. We most likely realize that we pay our electric bill based on the amount of electrical energy that we use. The billing is commonly based on kilowatt-hours (kW-h). This is 3600 kW-s (or kJ) or about 3412 BTUs. Other alternative energy units are listed in Table 1.5.

Although temperature is more commonly expressed in degrees Fahrenheit (°F) in the United States, we can readily convert to other units of temperature as shown in Table 1.5. Celsius or Centigrade (°C) is based on water freezing and boiling at 0 and 100, respectively, whereas 32 and 212 are, respectively, assigned on the Fahrenheit scale for these states of water. Both the °C and °F

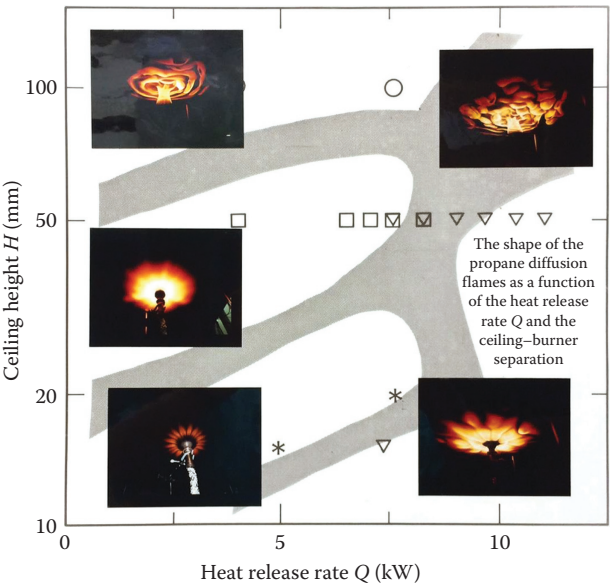


FIGURE 1.8
Ceiling flame plume interactions. (From Kokkala, M. and Rinkinen, W.J., *Some Observations on the Shape of Impinging Diffusion Flames*, Res. Rep. 461, VTT, Technical Research Centre of Finland, Espoo, Finland, 1987.)

TABLE 1.4

SI Quantities and Units

Quantity	Units
Force	N (newton)
Mass	kg (kilogram mass)
Time	s (second)
Length	m (meter)
Temperature	°C or K
Energy	J (joule)
Power	W (watt)
Thermal conductivity	W/m-K
Heat transfer coefficient	W/m^2-K
Specific heat	J/kg-K
Heat flux	W/m^2

scales do not start their zero designation as the lowest possible temperature. This designation (absolute zero) is where all thermal energy ceases. Therefore, alternative (absolute) scales of temperature begin with a zero designation from this point. When the interval is 1°F, this absolute scale is called the Rankine (°R) scale. Correspondingly, the Kelvin (K) scale is based

TABLE 1.5

Alternative Energy Units

1 BTU will raise 1 lb_m of water 1°F at 68°F (lb_m is a pound mass).
1 cal will raise 1 g of water 1°C at 20°C.
1 kcal will raise 1 kg of water 1°C at 20°C.
Some conversion factors for the various units of work and energy are as follows:
1 BTU = 778.16 lb_f-ft (lb_f is a pound force)
1 BTU = 1055 J
1 kcal = 4182 J
1 lb_f-ft = 1.356 J
1 BTU = 252 cal

TABLE 1.6

Temperature Conversions

°F—degree Fahrenheit: T (°F) = T (°C) (1.8) + 32
°R—degree Rankine: T (°R) = T (°F) + 459.67
°C—degree Celsius or centigrade: T (°C) = [T (°F) – 32]/1.8
K—Kelvin: T (K) = T (°C) + 273.15

on absolute zero for the Celsius scale. Table 1.6 gives conversion formulas between these various scales. It is important to appreciation that temperatures need to be in "absolute" units for certain formulas. For example, formulas that pertain to the relationship between electromagnetic energy (radiation) and temperature require the use of °R or K.

1.8.2 Symbols

Table 1.7 gives other conversion factors that may be useful. In addition, typically used symbols are assigned to the quantities. These symbols are used in this text and are fairly common in the fire literature, but they are not universal. Note that the dot over a symbol implies "rate" or "per unit time," and two accents imply "per unit area." The rate per unit area is commonly called flux. Greek symbols are also common, for example, ρ (rho) for density and α (alpha) for thermal diffusively. We will explain the significance of these qualities as we encounter them in our study of fire.

1.8.3 Scientific Notation

Finally, Table 1.8 lists terminology in scientific notation. This avoids many zeros in expressing numbers. For example, kW (kilowatts) denotes 1000 W or 10^3 W. Similarly, 10^{-3} W is one thousandth of one watt or one mW (milliwatt). This shorthand in terms of numbers is expressed as powers of 10, and prefix notation simplifies units of measure.

TABLE 1.7

Common Quantities, Symbols, and Conversion Factors

Length, l	1 m = 3.2808 ft
Area, A	1 m^2 = 10.7639 ft^2
Density, ρ	1 kg/m^3 = 0.06243 lb/ft^3
Energy, Q	1 kJ = 0.94783 BTU
Heat, q	1 kJ = 0.94783 BTU
Heat flow rate, $\dot{q}$	1 W = 3.4121 BTU/h
Energy release rate, $\dot{Q}$	1 W = 3.4121 BTU/h
Heat flux (heat flow rate per unit area), $\dot{q}''$	1 W/cm^2 = 3170 BTU/h-ft^2, (1 W/cm^2 = 10 kW/m^2)
Specific heat, c	1 kJ/kg-°C = 0.23884 BTU/lb_m-°F
Thermal conductivity, k	1 W/m-°C = 0.5778 BTU/h-ft-°F
Thermal diffusivity, α	1 m^2/s = 10.7639 ft^2/s
Pressure, p	1 Pascal (Pa) = 1 N/m^2 (1 atm = 14.69595 $lb_f/in.^2$ = 1.01325×10^5 N/m^2)

TABLE 1.8

Scientific Notation and Prefixes

Multiplier	Prefix	Abbreviation
10^{12}	Tera	T
10^9	Giga	G
10^6	Mega	M
10^3	Kilo	k
10^2	Hecto	h
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	Micro	μ
10^{-9}	Nano	n
10^{-12}	Pico	p
10^{-18}	Atto	a

Notes: For example, 10^3 = 1000 and 10^{-3} = 0.001; 1000 m = 10^3 m = 1 km = 10^{-3} Mm = 10^6 mm.

1.9 Summary

Fire is a chemical reaction, usually involving oxygen from the air, that produces enough energy to be humanly perceived. Typically, that energy release rate per unit volume is sufficient to cause a skin burn in seconds. The destruction by fire throughout history has been dramatic from the cause of the dinosaur extinction to conflagrations in large cities into the twentieth century. Natural events,

accidents, and war have produced devastating fire consequences. Statistics give us an appreciation for the loss and costs of fire around the world. The United States has one of the highest per capita deaths due to fire, as well as in expenditures for fire per GDP. Fire is rare in society, and consequently, there has not been a high incentive to study uncontrolled fire. However, research in fire has progressed throughout the world, and its results can be very useful to fire safety design practices and to fire investigation determinations. Visualization of fire phenomena is a first step in understanding and developing tools for fire protection. To be able to use these tools, the student must understand algebra, scientific units, and terminology. A goal to achieve by reading this book is to at least come to think of fire in terms of kilowatts.

Review Questions

1. Explain the difference between combustion and fire.
2. Can volcanoes and meteors cause fires?
3. Which country has the highest death rate due to fire? Do we know why?
4. What is a firestorm?
5. What are NFPA, IAFSS, NIST, and SFPE? What do they do?
6. Convert the following:

85°F	_____ °C
400°F	_____ °R
695°F	_____ K
30,000 BTU/h	_____ kW
0.0015 W	_____ mW
1385 W	_____ kW
6.5 W/cm^2	_____ kW/m^2

Activities

1. Find examples of the significance of fire in history.
2. Examine the statistics of fire and the attitude of society on fire safety.
3. Test the validity of fire statistics. For example, does the prevalence of electrical fire causes at night suggest something else? What percentage of accidental fires is actually reported?

4. Examine the SFPE Handbook, the proceedings of the IAFSS (Fire Safety Science series) on topics of interest to you. Discuss how you can benefit from this science. Is it understandable?
5. Identify fire organizations and laboratories around the world.

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2

Combustion in Natural Fires

Learning Objectives

Upon completion of this chapter, you should be able to

- Identify different forms of natural fire: diffusion flames, smoldering, and premixed flames
- Explain how a candle flame, a basic diffusion flame, works
- Recite quantitative aspects of natural fire
- Describe the processes leading to ignition and spontaneous ignition

2.1 Introduction

Natural fire processes can take different forms: diffusion flames, smoldering, and premixed flames. These are all chemical reactions that produce relatively high temperatures. Flames occur as gases. *Smoldering* involves the reaction of air with a solid. The smoldering chemical reaction occurs on the surface of the solid. For a flame, the chemical reaction is solely in the gas phase. As the reaction occurs at a high temperature, the reaction is fast and the extent of the reaction is relatively thin. *Diffusion*, or motion due to differences in concentration, is common to all flames. A pure *diffusion flame* occurs when the fuel and oxygen diffuse from opposite sides of the reaction zone. In the reaction zone, the fuel and oxygen are consumed, so their concentrations are zero there. In a premixed flame, the fuel and oxygen (or air) are already well mixed before combustion. The temperature of the mixture is low so as to not allow the chemical reaction to occur. But with a hot enough point in this mixture, a flame can emerge as a *premixed flame*. Typically, premixed flames are the ingredients of controlled combustion processes for heating and useful power. However, all diffusion flames are born from a premixed flame.

The term *spontaneous combustion* might be classed as a distinct fire process, but its occurrence results in either smoldering or a flame. This is simply an ignition process that occurs naturally due to the energy generated by a chemical reaction.

Let us examine these forms of combustion or fire in more detail.

2.2 Fire and Its Ingredients

A *chemical reaction* is a process that involves the change in a molecule by rearranging its atoms into different molecules. Combustion or fire is a chemical reaction involving the release of energy, some of which can be in the form of light. Combustion and fire are synonymous. A combustion reaction commonly involves the fuel molecule combining with oxygen to produce new molecules as *products*. A flame is combustion in which a fuel gas reacts with an oxidizer, commonly oxygen in the air. Smoldering is combustion in which a fuel reacts as a solid with oxygen in the air. To define a chemical reaction as fire or combustion, sufficient perceptible energy must be released. The rate of energy release per unit volume of the chemical reaction determines whether that reaction is fire. The size of the flame is not a factor. For a flame produced by a gaseous fuel combining with oxygen in normal air, the energy release is strongly dependent on the temperature of the molecules. Low temperatures produce an imperceptible amount of energy. Let us take a deeper look at this process.

2.2.1 Typical Temperatures and Energy Levels to Achieve Combustion

Roughly, the power production rate of a gaseous fuel reacting in air can be described in terms of how many kilowatts (kW) are produced in a cubic meter (m^3) of the mixture of fuel and air. So, consider such a small volume region composed of a mixture of fuel and air. The power production depends on the temperature of the mixture. The speed of the reaction and the energy released are the study of *chemical kinetics*, an entire branch of chemistry. Combustion reactions have high energy, and their speed increases extremely rapidly with temperature. Based on typical fuel–air mixtures, chemical kinetics allows us to estimate typical production rates according to the mixture temperature. These are ballpark values.

- At normal room temperature ~25°C, we have a power production rate of about 10^{-14} kW/m^3. The density of this mixture would be about 1 kg/m^3 and its heat capacity about 1 kJ/kg-°C. If all of this energy were absorbed by the mixture with no heat loss, the temperature rise can be estimated as $\frac{10^{-14}\ \mathrm{kW/m^3}}{1\ \mathrm{kg/m^3} \times 1\ \mathrm{kJ/kg\text{-}°C}} = 10^{-14}\ \mathrm{°C/s}$.

This temperature rise is imperceptible, and any heat losses are likely to not allow any increase in temperature. So, this mixture would very slowly react but not at a level to be called *combustion*.

- Let us raise the temperature of the mixture to say ~300°C, here chemical kinetics would indicate a faster reaction with an energy production rate of about 10 kW/m^3 (and a temperature rise of about 10°C/s). Now if heat losses are small, the temperature of the mixture would rise, and its energy production rate would rise accordingly. This feedback process between temperature and energy would make the process go faster and faster. As long as fuel and air are available, this acceleration process will reach a temperature level in which the production of energy is balanced by the heat loss. A higher temperature and energy production rate would be achieved. This process of moving from about 300°C to the higher reaction temperature is *ignition*.
- For combustion in air, a typical flame temperature is about 2000°C. As fuel and air are continuously supplied, we have about 10^{10} kW/m^3 (10^{10}°C/s). Here, the temperature would not continue to rise because the heat losses would exactly take away all the energy produced.

There are enormous differences in energy production over these temperatures. The differences highlight what it takes to initiate ignition and then to sustain a flame in air. It also shows that to have a "fire," a sufficient temperature is needed to set the process in motion. The process is sometimes called a *thermal runaway*, as it causes acceleration in temperature. This thermal runaway is the ignition process. It leads to a steady combustion state (at temperatures approaching 2000°C for reactions in air) where the flame will be sustained as long as fuel and air are continually supplied.

The combustion process for smoldering can result in a similar fashion. Smoldering on paper might been seen as a small (~1 mm) glowing region. It took some energy to raise the temperature of the paper to sustain this glowing region. However, with the paper at normal temperature in air, the same oxidation reaction may take years to even yellow the paper. Minimum temperatures to sustain smoldering can be as low as about 300°C, but glowing states could be as high as 1000°C. Temperature and the rate of energy production from the reaction define whether combustion will result for both a gaseous reaction (flame) and a surface reaction (smoldering). Typically, this temperature for a flame in air is about 2000°C, and for smoldering, it could be as low as 300ºC. These temperatures are consistent with the notion that if the chemical reaction temperature can cause a human skin burn, then it can be considered as *combustion*.

2.2.2 Fuel Chemistry

Most fuels are composed of carbon and hydrogen. These are called hydrocarbons and compose most of the fuels occurring in nature. Synthetic fuels, particularly plastics, can contain other elements such as oxygen, nitrogen, chlorine, and fluorine. When a fuel chemically reacts in air, new molecules are formed. The resulting molecules are called *products*. *Complete* or ideal reactions are those in which the products are molecules in their most stable state. This state will not allow their further oxidation. Complete chemical reactions for hydrocarbons would lead to the formation of water vapor and carbon dioxide. But most flame and all smoldering processes are not ideal in air. These reactions are interrupted and produce products that are not fully oxidized. Such reactions are termed *incomplete*. Incomplete products of combustion for hydrocarbons consist of carbon monoxide, hydrogen, and soot (mostly carbon). For the synthetic fuels, these products can also contain hydrogen chloride or fluoride instead of their pure elemental gases, and nitrogen-bearing fuels are likely to produce hydrogen cyanide instead of pure nitrogen gas. Factors that promote incomplete reactions are a reduction in the concentration of oxygen relative to normal air, turbulence in flames, heat loss, and smoldering in general.

2.2.3 Fire Triangle and Tetrahedron

The *fire triangle*, as shown in Figure 2.1, is a concept used to describe the components needed for fire. The elements of the fire triangle are essential to the existence of a fire. The triangle consists of (1) fuel combining with (2) oxygen in a chemical reaction to release (3) energy and other chemical products. The energy released by the reaction causes heat to be transferred to the solid or liquid fuel to maintain vaporization into gaseous fuel and to maintain the temperature to ensure that the chemical reaction can persist. If we take away sufficient fuel or oxygen, or reduce the energy by extinguishment or retardant agents, the fire will not survive. This applies to both smoldering and flaming.

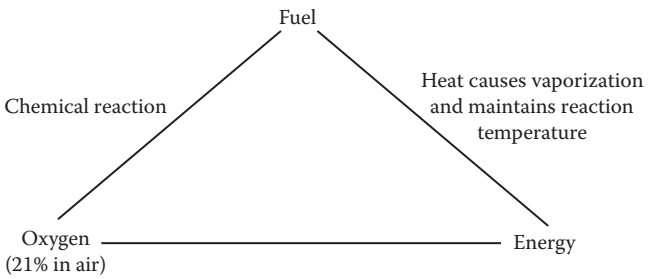

FIGURE 2.1
The fire triangle.

The fire triangle does not explicitly address the factors needed to make the combustion reaction occur in the first place. We saw from the subject of chemical kinetics that temperature is a big factor in initiating the combustion reaction. But what underlies this dependence on temperature? If the combustion reaction were put under a chemistry microscope, we would see much more than a simple transition of fuel and oxygen molecules directly changing to the resultant products. There would be a series of chemical reactions with many intermediate species. A sufficient temperature to produce a chemically active species might initiate the first step in the reaction. This active species would be unstable and prone to combine with another species. These unstable species are molecules without their full electron structure. They are called radicals and are highly reactive. The next step would produce more active species. This process is called a *chain branching reaction*. Specifically, chain branching is an intermediate chemical reaction that always produces two unstable species. If each radical, in turn, reacts with any intermediate molecule to form two more radicals (chain branching), multiple and increasing reactions can occur among the radicals and intermediates. This is a chain reaction of one reaction always leading to two. Eventually, a termination reaction is reached that ends the branching. As long as more active species are continually produced, the process accelerates. All of these chain reactions make the process fast. As energy is released, overall it would appear that temperature is driving the process. The way temperature affects the chemical energy production rates is a manifestation of chain branching. The subject of chemical kinetics studies the full chemistry of these chain branching reactions in combustion.

In examining the fire triangle, the factor of chemical kinetics does not show up. Yet, it is a vital factor in causing the combustion reaction to proceed. We cannot simply have fuel, oxygen, heat, and energy as the components of combustion or fire. The chemical kinetics must display sufficient energy and speed to support combustion. As a consequence, the *fire tetrahedron* has been introduced to students. This is a 3D object with four triangular sides. Each side is now designated as (1) fuel, (2) oxygen, (3) heat and energy, and now (4) chain branching reactions, or chemical kinetics.

The role of temperature is important to initiating chain branching. However chain branching could be initiated by an increase in pressure, as would be the case for some explosives that are pressure sensitive. But most often, it is the increase in temperature that sets the reaction in motion.

2.2.4 Combustion Time and Extent

Let us make some estimates of how fast the chemical reaction occurs in a flame, and how big is that reaction region. A temperature above normal air is needed to get to combustion. The minimum energy needed to achieve combustion is called the *activation energy*. For most hydrocarbons, the typical activation energy is about 160 kJ/mol. A representative molecular weight of a

typical fuel might be taken as 40 g/mol. So, this particular activation energy is 4 kJ/g. In comparison, it takes about 1.1 kJ/g to vaporize methanol and 2.3 to vaporize water.

Let us use 4 kJ/g as the activation energy to cause combustion. A mixture of fuel and air that would allow all of the fuel and oxygen to burn completely is called a *stoichiometric* mixture. Natural flames operate at this ideal mixture. A typical stoichiometric mixture for a hydrocarbon fuel is about 12 g air to 1 g fuel. So, we would have 13 g in this mixture. The activation energy for the mixture is 4 kJ/g fuel/13 g mixture/g fuel or 0.31 kJ/g mixture.

When a flame occurs we have about 2000°C and an energy production by the chemical reaction of about 10^{10} kW/m^3. At this temperature, the density of the mixture is about 130 g/m^3. The power produced per g mixture is 10^{10} kW/m^3/130 g/m^3 or 7.7×10^7 kW/g. Dividing this into the activation energy gives a time for a combustion of about 4×10^{-9} seconds. Of course, heat would be lost and less than 10^{10} kW/m^3 would be retained by the mixture. But this simple estimate illustrates that the time for combustion to occur is very, very small. Indeed, one might say that in a flame, when a fuel and oxygen molecule come together there is almost instant chemistry. Yet underlying all of this is complex chemical kinetics.

Let us stick with this estimate for the time for combustion as 4×10^{-9} seconds. In this time, oxygen and fuel are being consumed, and diffusion is the primary manner in which these species are moving. They begin with their initial concentration and move to a point of zero concentration. The laws of diffusion govern the distance a species moves in a given time. An approximate estimate is distance equals the square root of the product *diffusivity* × time. The diffusivity of this mixture at 2000°C is about 8×10^{-4} m^2/s. The estimated distance over which the combustion occurs is about 1.8×10^{-6} m. This is a very small region.

These estimations were very simplified. A complete calculation must take into account the actual kinetics, the heat transfer, and the diffusion of all species. But, in general, combustion occurs quickly (less than a second), and the combustion region is very thin (less than a millimeter). Flow can disturb the image of a flame, and in a turbulent flow the thin regions of the flame become a tangled web. This projects a more global image of the ensemble that we might call *the flame*. However, it is composed of small flame pieces.

2.2.5 Types of Fire

We can categorize fire into three distinct phenomena:

1. Diffusion flames
2. Smoldering
3. Premixed flames

Diffusion flames represent the predominant category. It is the building fire, the forest fire, or the lit match. Smoldering can initiate or can follow the death of a diffusion flame. It is the glowing embers of the tragic house fire, the result of a lightning strike to the forest bed, or the glow of a blown-out match flame. In both diffusion flames and smoldering, the fuel and oxygen are initially separated. Some transport process is needed to bring them together. On the other hand, premixed flames have their fuel oxygen mixed before the combustion occurs. Premixed flames represent controlled combustion processes such as in a gasoline internal combustion engine with spark ignition or in a diesel engine with no sparkplug. It also represents the incipient flame that occurs in the ignition of solids or liquids. Then a diffusion flame emerges. A fuel and oxidizer can also be premixed as solids. This state represents propellants and some explosives. As these solid components create a combustion reaction, gaseous products are likely to be released, and they must be constructively transported away as in propellants. In explosives, these gases are trapped in the solid explosive mixture and lead to increases in pressure that accelerates the reaction even further. Let us examine these forms of combustion.

2.3 Diffusion Flames

A diffusion flame is a combustion process in which the fuel gas and oxygen are transported into the reaction zone due to concentration differences. This transport process is called diffusion and is governed by Fick's Law, which says that a given species will move from a high to low concentration in the mixture. In connection with fire, species are the components of the reaction, for example, oxygen, fuel, CO_2, and other components comprising the reactants and products. To understand the nature of diffusion, consider a drop of blue ink in a glass of still water. Eventually, the dye droplet will disperse into the water to give a uniform blue tinge. This motion of the dye into the clear water is diffusion. Oxygen in air will move to the flame zone where it has a concentration of zero since it is consumed in the reaction. Fuel is transported into the opposite side of the flame by the same process. The combustion products diffuse away from the flame in both directions. This process is illustrated in Figure 2.2.

Most natural flaming fires are diffusion flames. A common example is the flame of a match or a candle (Figure 2.3). In a candle, the flame melts the wax, and the melt is transported up the wick by capillary action. The flame then evaporates the wax, and the gaseous fuel diffuses into the flame where it meets oxygen. For a wooden match flame, the wood is decomposed by the heat of the flame into gaseous fuel and char. This thermal decomposition process of a solid is called *pyrolysis*. A candle flame is an example of a

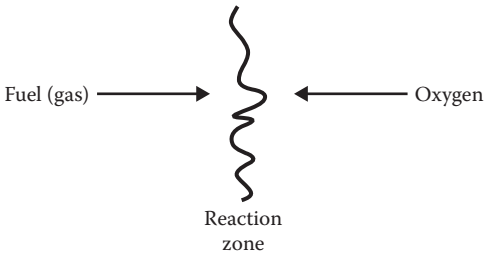

FIGURE 2.2
Schematic of a diffusion flame.

FIGURE 2.3
A candle, an example of a diffusion flame.

laminar diffusion flame governed by pure molecular diffusion. Any flame higher than approximately 1 ft will naturally possess random fluid mechanical motion, illustrated by visible eddies in the smoke and flame. This is called *turbulence*, in contrast to the orderly motion of a laminar flow. So, most fires due to size are turbulent diffusion flames (Figure 2.4). Smoke from a large chimney has this turbulent character, and a smoke filament from a cigarette in a still room, which begins as a laminar flow, then clearly breaks up after rising about 1 ft to become turbulent (Figure 2.5).

Gravity influences the shape of diffusion flames and profoundly affects fire processes in general. Because fire creates high temperatures, the hotter (lighter) gases rise as a result of buoyancy caused by gravity. The ensuing flow distorts the flame, and eventually, flow instabilities cause turbulence. Turbulence is due to disturbances, arising naturally, that excite the flow at its natural frequency. This same phenomenon occurs when an unbalanced

FIGURE 2.4
A turbulent diffusion flame.

tire begins to vibrate erratically at a speed associated with the wheel's natural frequency. The mechanical constraints restrict the wheel from ripping off the vehicle. Similarly, fluid friction keeps the erratic fluid's turbulent motion within limits. The cigarette smoke plume in Figure 2.5 clearly displays the onset of turbulence at a point where erratic flow vibration occurred. The size of the turbulent large swirls (eddies) is constrained by the fluid's viscosity. Accordingly, buoyancy and turbulence are two factors that control fire and its associated flows. It is interesting to contemplate the behavior of diffusion flames in a spaceship in which gravity and therefore buoyancy are negligible. Only flow from a fan can disturb this flame and augment the inherent diffusion process. Without the buoyancy of gravity, the flame would not elongate. Figure 2.6 is a candle flame that was photographed aboard the International Space Station under nearly zero gravity. As seen, the flame is nearly symmetrical about the wick, compared to the flame in normal gravity. In microgravity, diffusion is independent of direction to give the spherical shape.

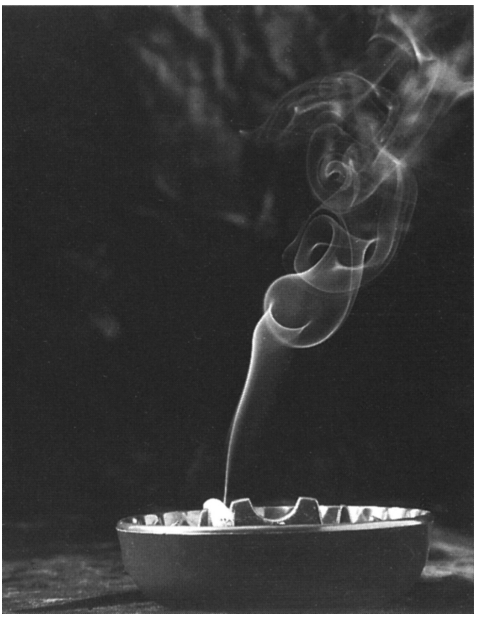

FIGURE 2.5
Cigarette smoke.

FIGURE 2.6
Candle flame in normal and microgravity. (From National Aeronautics and Space Administration Lewis Research Center.)

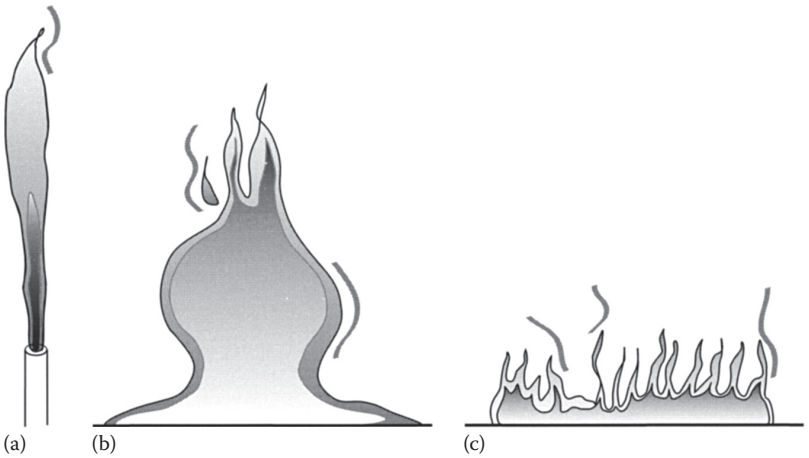

FIGURE 2.7
Diffusion flame shapes: (a) jet flame, (b) liquid spill fire, and (c) forest fire.

The general shapes of diffusion flames are illustrated in Figure 2.7. Three types of diffusion flames are shown: (1) a jet flame, (2) a moderate pool fire, and (3) a very large fire. Natural fires involving liquid or solid fuels have very low velocities at the fuel base (~1 cm/s), but a high-pressure gaseous fuel source can initiate fuel at much higher velocities. For such high-velocity jet flames, buoyancy effects can be negligible. Jet flames have the characteristic that as the velocity is increased, for a given port diameter, the jet flame will eventually reach a fixed height. Pool fires with characteristics as shown in Figure 2.7b are more representative of normal burning commodities. They achieve heights associated with their fuel supply and continue to get taller as long as buoyancy controls their air supply. Fires over large areas, such as forest fires or city conflagrations, have short flames relative to their base. Their flame height is more controlled by the air flow that is drawn around its perimeter. As air supply can be limited around the perimeter, these flames can be drawn down from above as well as drawn in from the sides. Figure 2.7b will be the principal focus of our attention and represents diffusion flames associated with commodity and furnishing fires.

2.3.1 Candle Flame

The candle flame provides most of the essential features of natural fires and a diffusion flame. It will be our learning tool. We are not original in this approach because we will repeat some of the experiments created by the nineteenth-century scientist, Michael Faraday (Figure 2.8). These experiments were presented at the Royal Institution in London as a science show for the public. Known as the Christmas Lectures, they were very popular

The Scientific Discoveries of Michael Faraday

1820	discovered two unknown chlorides of carbon
1821	discovered electromagnetic rotation—set up an experiment in which a wire carrying an electric current rotated in the field of a horseshoe magnet.
1823	liquefied chlorine
1825	isolated benzene
1831	demonstrated the principle of electromagnetic induction, the production of electric current by a change in magnetic intensity
1844	discovered the rotation of the plane of polarization of light in a magnetic field

FIGURE 2.8
Michael Faraday and his discoveries. (From Faraday, M., *Faraday's Chemical History of the Candle*, Chicago Review Press, Chicago, IL, 1988 [orig. 1861].)

with children and have been archived in a book that is still available today.[1] Some of these lectures are remarkable in their simplicity, yet powerful in their illustration of the basic principles of flames.

It is astonishing to those who study fire to see how Faraday appreciated the workings of a candle and its implication to the science of fire. These thoughts are expressed in his opening remarks at the convening of the Christmas Lectures:

> I propose to bring before you, in the course of these lectures, the Chemical History of a Candle. There is not a law under which any part of this universe is governed which does not come into play and is touched upon in these phenomena. There is no better, there is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomena of a candle.[1]

Light a candle and observe the processes that create the sustained flame. As illustrated in the sketch in Figure 2.9, you can see several things. The yellow and blue zones constitute the flame (the former, diffusion; the latter, premixed). The wick is actually designed to curve so that the flame "clips" off the wick and limits its height. Why is not the wick destroyed throughout

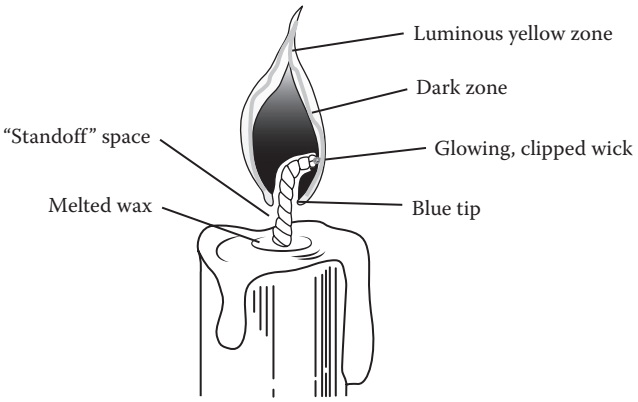

FIGURE 2.9
Characteristics of a candle flame.

the flame? What is the purpose of the wick? With some thought, it can be deduced that the heat of the flame melts the wax, and the melt soaks the wick by capillary action, like water feeding tree leaves. The melt keeps the cotton relatively cool and intact. The heat from the flame evaporates the melt and diffuses the fuel gas into the luminous flame zone. There it finds oxygen having diffused from the other side. Buoyant flow elongates the candle flame, but the flow path is small enough so that laminar flow is maintained within the flame. However, as the hot combustion gases rise from the flame, they become turbulent. This turbulent phenomenon can be seen by projecting collimated light (from a slide projector or strong flashlight) at the flame and onto a white screen. This is shown in Figure 2.10.

FIGURE 2.10
Image of flame (soot) shadow and shadowgraph white-dark projection of turbulent eddies.

There are several shadow images on the screen. Distinctly, the solid candle and the wick block the light and form a clear black shadow image. Looking closely, a shadow-like image of the luminous portion of the flame also appears on the screen. What might cause this flame shadow? Some solid ingredients must be blocking the light through the flame. These particles must form within the flame. Looking more closely about the shadow of the luminous image on the screen, white curves are seen surrounding this image. These white lines result from the refraction of light rays as they bend through the flame. Where the temperature changes the most quickly (the edge of the hot region), the light is reinforced to give a white image. This effect of producing the white images is a technique known as a shadowgraph and marks the edge of the plume around the flame. The turbulent eddies of the plume region above the flame can also be seen in the shadowgraph above the flame. These images are very revealing for the flame. It shows the luminous region blocks light, some distance lateral from the luminous region it is still hot (due to conduction from the reaction), and turbulent regions of hot and cold form in the plume above the flame.

Now place a metal screen (typical window screen mesh, but not aluminum) into the flame as shown in Figure 2.11. The metal screen cuts the flame, extinguishing further combustion. Why? Describe the luminous flame cut.

Combustion reactions can only be sustained if the flame temperature is high enough, typically greater than 1300°C. As the height of the screen is varied in the flame, black smoke is released with the screen high in the flame and white or gray "smoke" with the screen near the top of the wick. What do these colored smokes imply? Collect the black smoke on a piece of white paper, being careful not to insert the paper in the flame. What is collected on the paper? Where do these black particles originate? Find that region in Figure 2.9. Blow out the flame and observe the color and character of the smoke that momentarily emanates from the wick. How does this compare to the white smoke resulting from the low screen position?

Relight the candle. After the flame steadies, insert a glass dropper into the region where you think the white smoke originated. Extract the white smoke into the dropper tube. Squirt this white gas across the top of the flame (Figure 2.12). It should ignite and resemble a small flame thrower. What were these white vapors? It is fuel vapor that has condensed into small droplets, appearing as white. Clouds in the sky are white for their condensed water droplets. A cloud of droplets will scatter light, and it will appear as "white."

To confirm your conclusion that the white vapor extracted is fuel, blow out the candle flame again, and quickly try to ignite the white vapors coming from the wick. You will see a flame propagate down this vapor

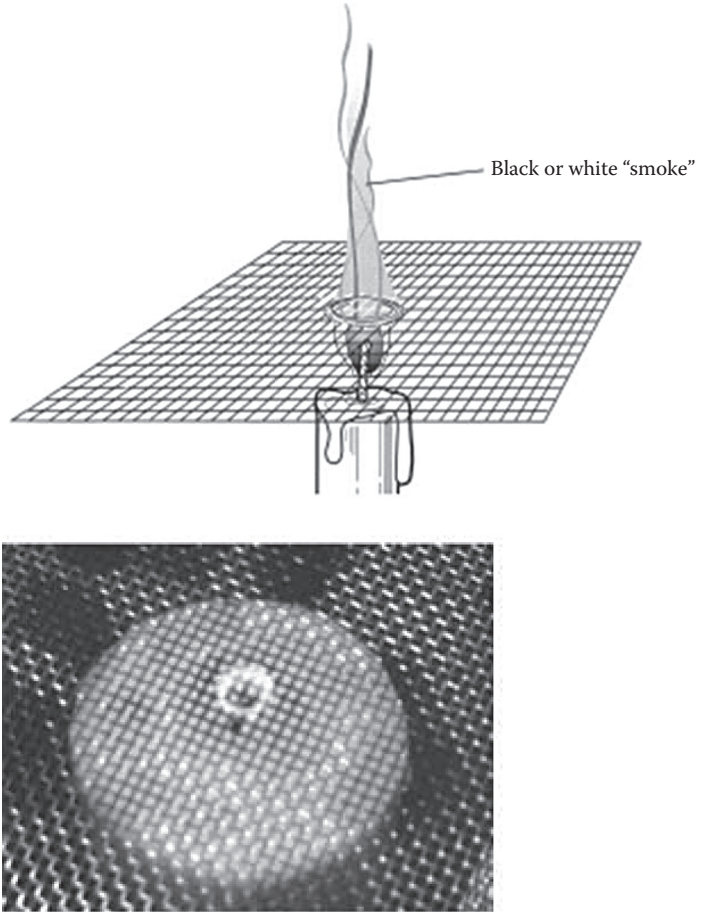

FIGURE 2.11
Sketch and photograph of metal screen cutting the flame.

trail and anchor on the wick. This propagating flame is a premixed flame (we will explain this further in a bit); the anchored flame is, of course, our diffusion flame.

Review all of the information deduced about the candle flame and you should have a good understanding of the diffusion flame and fire. You may wish to consult Faraday’s text for more informative experiments with the candle.[1] These experiments are simple, and I encourage you to try them for yourself. You may even invent new procedures to learn more about fire from the candle flame.

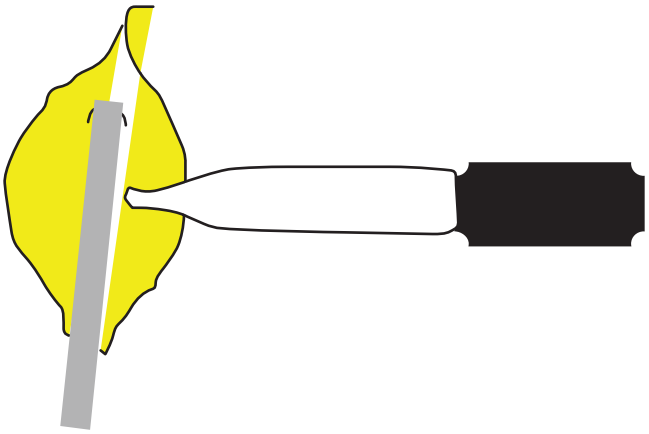

FIGURE 2.12
Extracting interior flame gases.

2.3.2 Anatomy of a Diffusion Flame

More sophisticated experiments with a laminar diffusion flame using methane (CH_4) as the fuel have been conducted by Kermit Smyth and coworkers.[2,3] Their flame is formed from controlled flows of CH_4 and air, as shown in Figure 2.13. The burner is a slot burner, so it is planar in character compared to the cylindrical character of the candle, but the flame dynamics are similar to the candle. Various point measurement techniques were used in the flame to quantitatively reveal its anatomy. We can relate these measurements to what we have deduced from the candle experiments. Now our qualitative observations can be quantitatively presented. These quantitative results will be displayed for a height 9 mm above the burner. This position is arbitrary, representative of examining a "horizontal cut" through the region where a diffusion flame exists.

Thermocouple measurements of temperature across the flame region are shown in Figure 2.14 at the 9 mm height. Other heights within the luminous flame region will show a similar bimodal, two-hump pattern. These 9 mm measurements are indicative of the two sides of the diffusion flame. The maximum temperature indicates the location of the chemical reaction. The combustion needs fuel and oxygen as well as a sufficient temperature to initiate and to persist. The drop-off in temperature on both sides of the peak indicates heat loss; however, a high temperature is still achieved to preserve the flame. Earlier, it was indicated that this required temperature is about 2000°C. The thermocouple probe used here will lose some heat and slightly cool the flame; therefore, it is difficult to accurately measure the highest temperatures indicative of the reaction zone. The indicated measured peak temperature of approximately 1700°C is likely to be more like 1900°C–2000°C. Nevertheless, this very-high-temperature region measured is indicative of

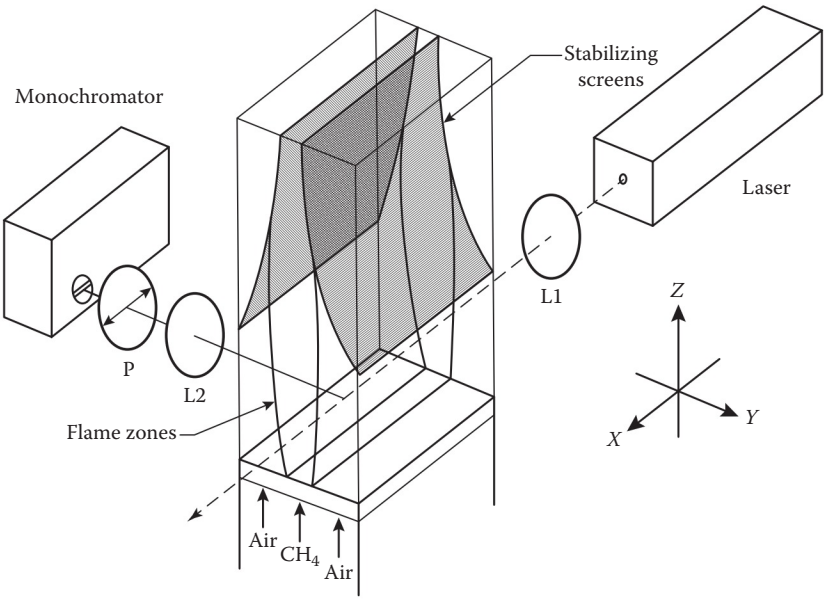

FIGURE 2.13
Arrangement of a slot burner and point measurement techniques. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

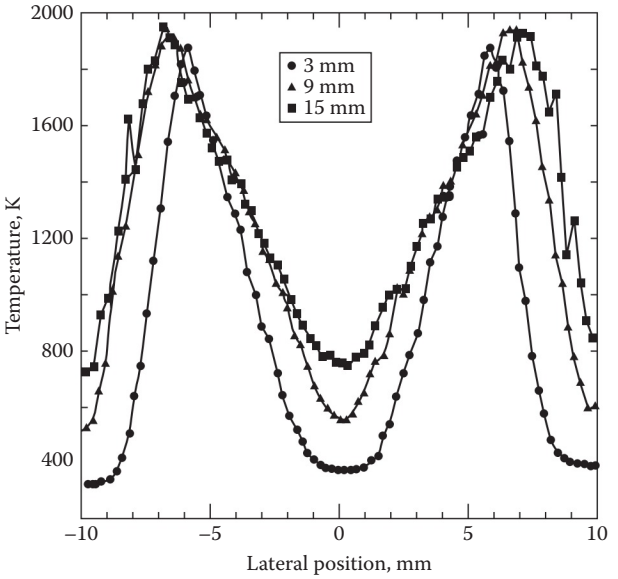

FIGURE 2.14
Temperatures across a laminar diffusion flame. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

the chemical reaction zone of the flame. This was the luminous yellow shell of the candle flame. In Figure 2.14, the width of this peak region is about 1 mm. Recall observing the candle flame through the top of the metal screen that cuts it horizontally. The luminous region was also about 1 mm.

The rest of the temperature graph shows the regions away from the reaction or flame zone. The interior temperatures are due to heat conducted inward. This heat would be what the candlewick would need to sustain the evaporation of the fuel. The outer-wing temperature should eventually become the temperature of the pure air of about 25°C (298 K). While this is not shown directly in the graph, it would occur about 5 mm from the flame. The shadowgraph image for the candle flame would mark the onset of pure air.

The corresponding vertical flow speed is shown in Figure 2.15. These flow speeds are principally due to buoyancy. Indeed, the temperature is directly responsible for these vertical speeds. The peak of 80 cm/s is about 1.8 mph; a light breeze.

Using special laser-optical techniques, Smyth and coworkers were able to image the visible flame, OH radicals, and soot. The OH radicals are indicative of short-lived chemical species in the heart of the combustion reaction. Once they die out, the flame chain branching reaction dies. They extend to the air side of the flame. The soot, or black smoke of the candle experiments, comes from within the (luminous) flame zone. This is clearly seen in their images

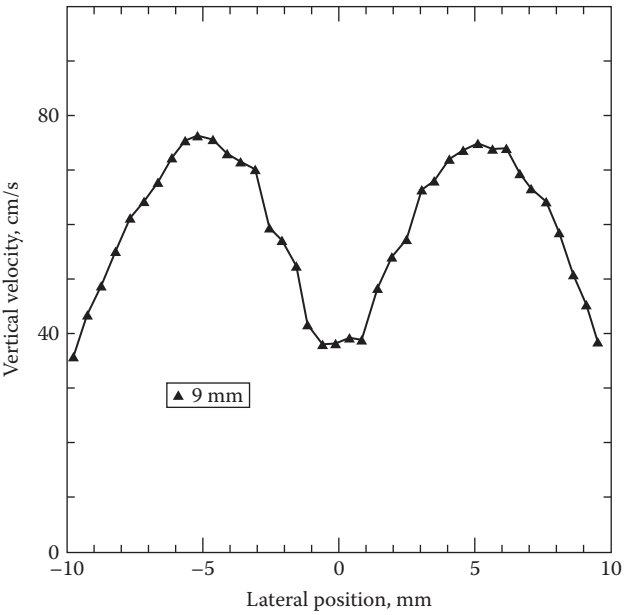

FIGURE 2.15
Vertical velocity in a laminar diffusion flame. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

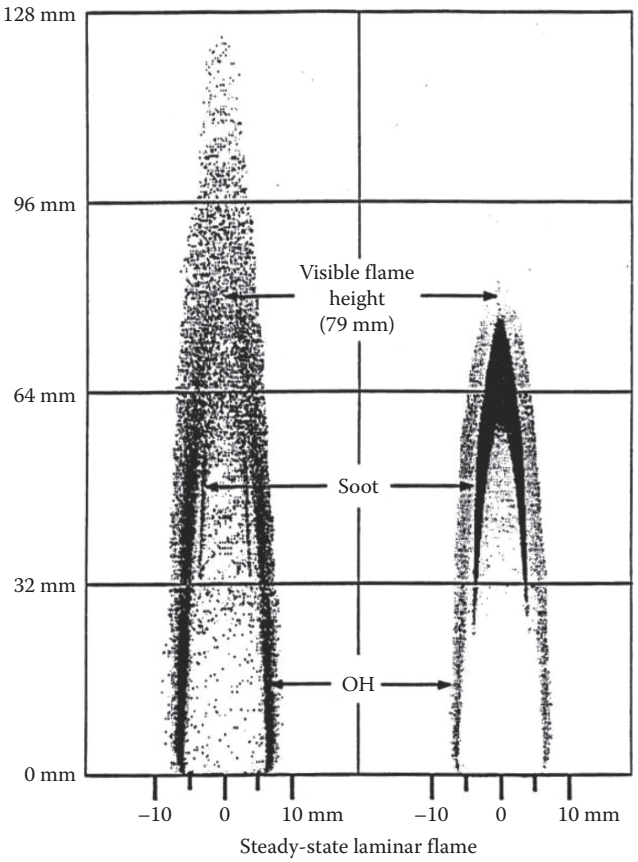

FIGURE 2.16
Soot and flame reaction zone locations in a laminar diffusion flame. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

illustrated in Figure 2.16. While that figure is an artistic rendition of their results, their measurement techniques were quite sophisticated. The shadow of the soot particles in the candle flame (Figure 2.10) is indicative of their soot region shown here.

The soot is formed on the fuel side of the diffusion flame. It results from a complex process as the original fuel (CH_4) is heated on diffusing toward the flame. This intense heating results in cracking the CH_4 molecules into many other hydrocarbon molecules. As acetylene (C_2H_2) and other precursors form, soot (mainly C atoms) is produced. The soot (a solid formed from gases) migrates through the reaction (flame) zone, is oxidized (mainly by OH), and is consumed. We see this oxidation by the yellow (incandescent) glow of the visible flame. As the soot is being oxidized, it is exposed to the very high temperatures of the reaction zone. The color of orange-yellow is

indicative of a surface at about 2000°C. This is why flame has that color. In this flame, as well as the candle flame, nearly all the soot is consumed before the reaction zone ends. The visible flame height nearly coincides with the end of the soot height (Figure 2.16), and the OH zone is slightly above this height.

If we "tear" the flame by "stretching" it (e.g., abruptly pull the candle flame or disturb it by pulling a small probe through it), soot can escape through the tear. Again, this illustrates that the soot formation is on the fuel side of the flame. For a heavily sooting fuel, all the soot may not be oxidized before the end of the reaction zone; then soot escapes as black smoke. However, even for fuels with low soot-forming tendencies, as long as they contain carbon, insufficient air supply to the flame will lead to escaping soot.

Let us examine the other species that occur in this flame process. Some of these are shown in Figure 2.17. Smyth et al. took the measurements at the same 9 mm above the fuel port.[2] The concentrations are given in mole fraction, which is equivalent to *volume fraction*. Volume fraction is the volume of the species gas to volume of the mixture at the same temperature and pressure. For example, if one extracts the oxygen from air and let it come into balance with the air pressure, the ratio of its equilibrated oxygen volume to the volume of the mixture (air) is the volume fraction. Note the oxygen (O_2)

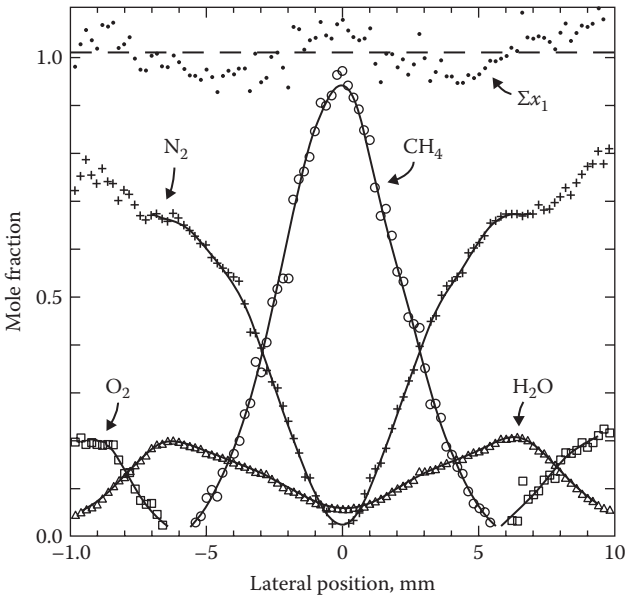

FIGURE 2.17
Major species formed in a laminar diffusion flame (CH_4) at 9 mm. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

in pure air is at 0.21 volume fraction with the nitrogen (N_2) making up the remainder 0.79. These values are measured at the extreme left and right wings in Figure 2.17. The fuel (methane, CH_4) has a volume fraction of nearly 1 (all fuel) at the center. As 100% methane flows from the slot, at 9 mm above the slot it is still nearly 100%. We see that the fuel and oxygen reach zero at approximately 6 mm along the lateral position, the peak of the combustion zone. This zone is about 1 mm in width at a height of 9 mm above the fuel source. The water vapor (H_2O) is also at maximum at 6 mm. Along with carbon dioxide (CO_2), water vapor is a principal compound formed and released into the atmosphere as a product of combustion. Figure 2.18 shows the results for CO_2 along with other compounds, namely, carbon monoxide (CO) and hydrogen (H_2), which do not survive to be released into the atmosphere. As the soot and OH would fall to zero, as the end of the reaction zone is reached at about the 6 mm lateral position, the other under-oxidized species, such as CO and H_2, form CO_2 and H_2O.

The concentration of species varies laterally because their relative proportions change due to the production and destruction processes of the chemical reaction. As their concentrations change, diffusion also occurs among them. Figure 2.19 qualitatively illustrates the migration of species taking place in the complex chemical processes of the flame. Superimposed

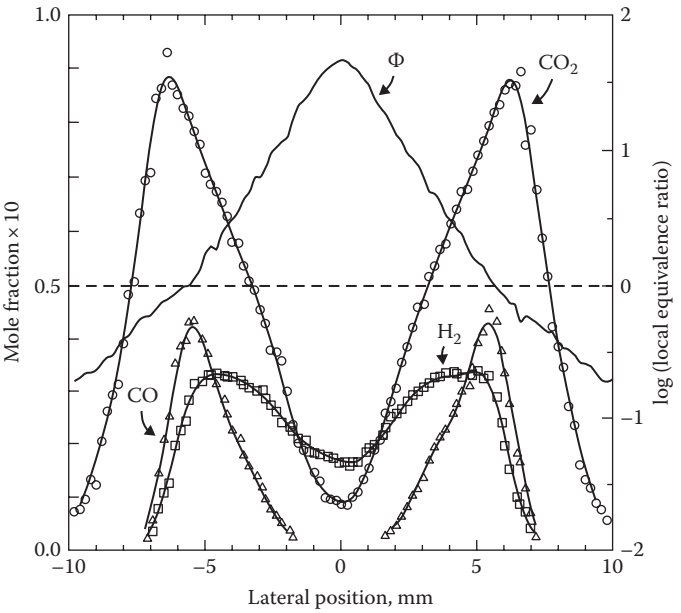

FIGURE 2.18
Additional major species formed in a laminar diffusion flame (CH_4) at 9 mm. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

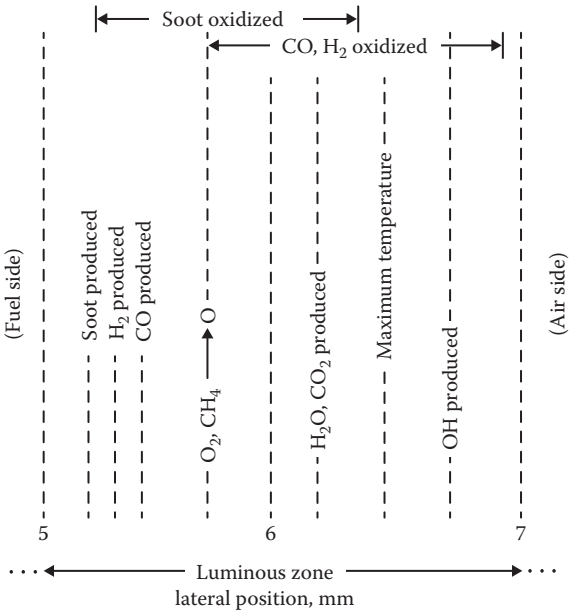

FIGURE 2.19
Qualitative chemical processes in a CH_4 laminar diffusion flame.

on these chemical processes are the physical processes involving (1) diffusion of species, each migrating toward its lowest concentration; and (2) motion due to buoyant flow caused by temperature. Due to cracking and synthesis of the CH_4, as the heat from the combustion process is conducted to the diffusing CH_4 molecules, other hydrocarbons, some of which are shown in Figure 2.20, are formed in reactions preliminary to combustion. These compounds are "minor species," achieving short-lived concentrations of 0.005 mole fraction at most before being completely oxidized. Returning to Figure 2.19, between about 5 and 7 mm, or over 2 mm, the fuel "cracks," soot forms, species come and go, and eventually OH dies out. The entire process that spans at about 2 mm with the more intense reaction (flame) is dispersed over about 1 mm.

2.3.3 Turbulent Diffusion Flames

We have seen that in the plume above candle flame becomes turbulent in less than 1 ft of height. This is typical of fire under normal buoyancy conditions. Therefore, nearly all natural diffusion flames arising due to accidental fires are mostly likely to become turbulent. The laminar flame processes we have just reviewed must be viewed as fluctuating erratic processes within a turbulent flame. The processes depicted in Figures 2.14 through 2.20

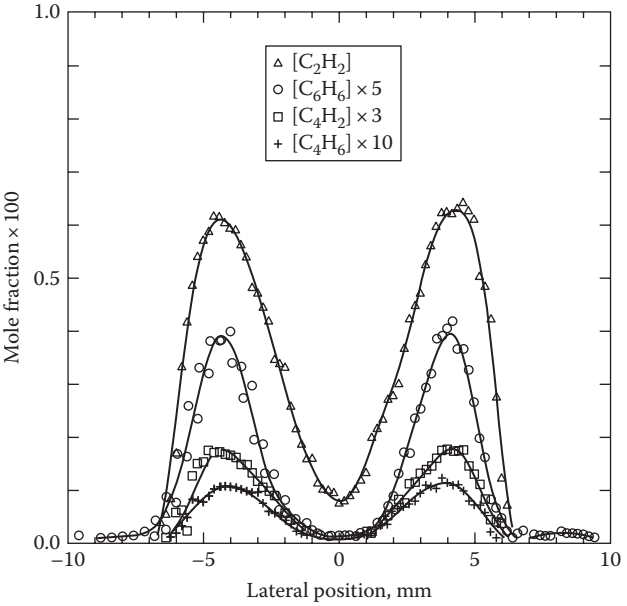

FIGURE 2.20
Minor chemical species in a CH_4 laminar diffusion flame. (From Smyth, K.C. et al., *Combust. Flame*, 62, 157, 1985.)

are pushed and pulled in space, blurring the values of the concentrations. Figure 2.21 is a rendition of a temperature measurement of a turbulent flame. As the flame moves about the probe, the temperature fluctuates over the extremes measured for the still laminar flame of Figure 2.14. The turbulent flame can be conceived as an ensemble of laminar flames moving chaotically in space. An ordinary probe is not likely to keep up with these extreme and rapid changes. It will tend to experience an average value. Instead of discerning a clear temperature in the 1 mm reaction zone, the measurement probe will experience high and low temperatures, with averages approximately 800°C–1200°C. Thus, peak temperature conditions of a laminar flame will not be discerned in a turbulent flame. This fluctuating effect will apply to all of the species as well as temperature. Although the turbulent flame will not give on average the temperatures and concentrations of its laminar counterpart, the ingredients of the laminar flame can be used to understand the more complex turbulent flame. A complication is that due to all of the fluctuating effects some fuel and oxygen may actually mix before they burn. This is now a premixed flame, not a diffusion flame. Thus, a turbulent flame is quite complex, and its prediction is still a source of active research.

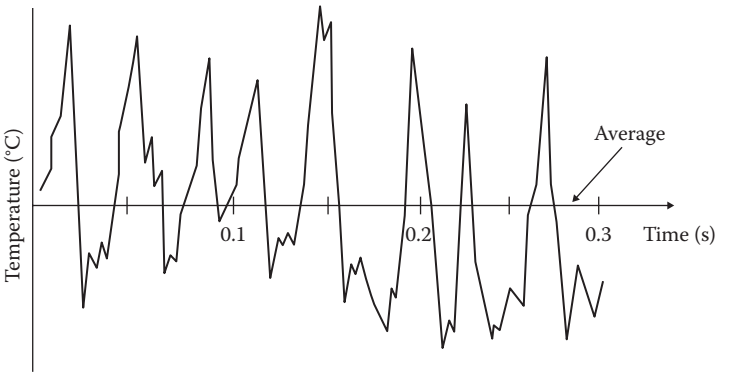

FIGURE 2.21
Turbulent temperature fluctuations in a flame.

2.4 Premixed Flames

A premixed flame is the second type of combustion we can call fire. A premixed flame is a combustion process in which the fuel gas and air (or oxygen) are first mixed before ignition and propagation occur. In a diffusion flame, both laminar and turbulent, the fuel is supplied in a distinct stream, and air is then mixed into it as it burns. In a premixed flame, the fuel and oxygen, or air, are mixed, then burning occurs within that mixture. In a confined space, such a combustion process can cause a rapid pressure increase that manifests itself as an explosion. If sufficient pressure builds up behind the propagating flame, it will accelerate the flame. At a higher speed, turbulence will ensue and increase the reaction rate. Eventually, the flame speed can reach the speed of sound, and with further increases, a shock wave will form ahead of the flame. That shock wave introduces now higher temperature and pressure for the fuel and oxygen supplied into the flame. We know that the chemical reaction rate is increased as temperature and pressure rise. This leads to a feedback effect. The speed of the flame increases, and a stronger shock is formed with yet higher temperature and pressure across it to feed the flame. The end result will produce an extremely high flame speed with a shock wave preceding it. This event is then called a detonation. Such an event has great damage potential; however, even the nondetonating (deflagration) premixed flame in a confined space can cause significant damage due to pressure rise. Both events will be perceived as an explosion. While we are considering flames here, premixed combustion systems can exist as solids (e.g., dynamite, rocket propellants, etc.). The dynamics of premixed flames can be used to explain these systems as well.

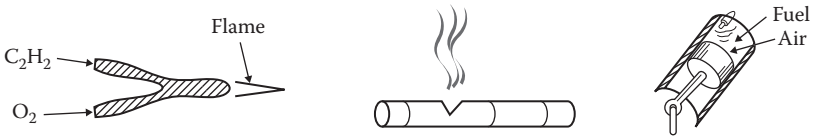

FIGURE 2.22
Examples of premixed flames.

As with the diffusion flame, it is sufficient to understand premixed flame systems in general by studying the simplest system. So, the onset of premixed flames will be considered. These are laminar flames with relatively slow speeds. Moreover, premixed flames are common to most useful controlled combustion processes. Figure 2.22 shows common examples of where premixed flames occur. Acetylene mixed with oxygen forms a very high-temperature flame for welding and cutting metals. (By the way metals can burn, too, especially under pure oxygen.) A gasoline internal combustion engine vaporizes the fuel in a chamber with air and an electric arc ignites the mixture. An accidental scenario is depicted by the methane leak. The methane mixes with air, and that mixture could find a source of ignition. The premixed flame will propagate from the ignition source back to the leak. A diffusion flame can then result at the leak.

2.4.1 Laminar Flame Propagation

Returning to the candle experiments: When the flame is blown out, the white wax–fuel vapor mixes with air as it rises in its distinct plume. Attempts to reignite the plume will succeed provided the ignition flame is placed in the plume stream at the right concentration. Gaseous fuels will ignite within distinct fuel concentration limits. For every fuel gas in air, there is an upper (UFL) and lower (LFL) flammable limit concentration in which flame propagation can occur. Flammable here means that the mixture will ignite and propagate at these concentrations. The speed of propagation for a laminar flame is relatively low, less than 1 m/s. It is the speed that the flame will travel along the white vapor of the blown-out candle flame. Another illustration of this speed can be perceived from the candle experiment with the metal screen cutting the flame. This is shown in Figure 2.23. In this figure, the flame suspended above the screen results from a plume streak of white fuel vapor rising up from the center of the diffusion flame around the candlewick below the screen. When that suspended flame was ignited, white fuel and air were moving vertically upward toward it. Once ignited, the flame became suspended because its propagation speed down into the white fuel–air streak was equal to the upward speed of the plume streak. This is a premixed flame in the same suspension that would occur on a stovetop premixed burner.

FIGURE 2.23
Floating premixed flame (a) above screen that clipped the candle flame and (b) premixed flame above screen and diffusion flame below screen.

A mixture with fuel within the flammability limits will allow flame propagation once ignited. These values (usually calculated at 25°C in air at normal pressure) vary slightly with the temperature as shown in Figure 2.24. The concentration over which flammability is possible will increase as the mixture temperature increases. At a given mixture temperature, we see that there is an upper and lower flammability limit. In this range, this means a small energy source will initiate sustained propagation at a speed that would be in the range of about 25–100 cm/s. If the temperature of the fuel mixture

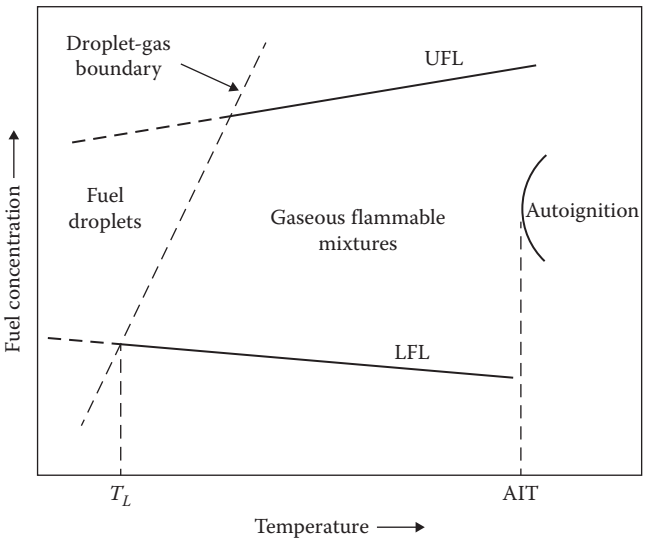

FIGURE 2.24
Limits of flammability in air showing the effect of temperature from Zabetakis. (From Zabetakis, M.G., Flammability characteristics of combustible gases and vapors, Bulletin 627, Bureau of Mines, U.S. Department of the Interior, Washington, DC, 1965.)

is varied, the LFL and UFL change slightly as seen in Figure 2.25. But at very low temperatures, the fuel may be condensed in the form of droplets. This droplet mixture also has flammability limits. The temperature (T_L) just when the fuel condenses to a liquid at the LFL is called the flashpoint. We discuss this phenomenon further when we examine the ignition of liquids in Chapter 4. Although this ignition process requires an energy source such as a flame or electric discharge, it is quite small—less than 1 mJ (which is that amount of energy to raise 1 g of water less than 0.001°C). In contrast, at a high enough temperature, the fuel–air mixture can ignite without any energy source. The lowest temperature to cause this spontaneous ignition phenomenon is called the *auto-ignition temperature* (AIT), also illustrated in Figure 2.24.

The AIT reported for a fuel is representative of the fuel in the gaseous state in the presence of air within its flammable limits. It is usually measured in a specific size vessel and in general depends on size. So, there is not a distinct AIT for a given fuel. It can vary depending on the circumstances of heating. But as temperature is critical to initiating the process of combustion, this initiation temperature is roughly in the range of 300°C–600°C for typical hydrocarbon fuels mixed with air. At the specific AIT, the mixture will reach combustion. Table 2.1 gives some typical values for the AIT, along with the flammability limits needed for propagation.

2.4.2 Flame Temperatures

Once ignited, it is interesting to consider the temperature that the flame will reach. A fuel gas burning in air must heat up the nitrogen in the air, as it does not take part in the chemical reaction. If the nitrogen is not present and the fuel

TABLE 2.1

Flammability Limits of Gaseous Fuels in Air at Normal Atmospheric Temperature and Pressure

Fuel	LFL (%)	UFL (%)	AIT (°C)
Acetylene	2.5	100	305
Benzene	1.3	7.9	560
n-Butane	1.8	8.4	405
Carbon monoxide	12.5	74	609
Ethylene	2.7	36	490
n-Heptane	1.05	6.7	215
Hydrogen	4.0	75	400
Methane	5.0	15.0	540
Propane	2.1	9.5	450
Trichlorethylene	12	40	420

Source: Beyler, C.L., Flammability limits of premixed and diffusion flames, Chap. 2–9, in: DiNenno, P.J., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

burns in pure oxygen, the flame would reach a much higher temperature. The flame temperature ultimately depends on the energy released in the combustion reaction, how much gas must be heated, the actual reaction progress, and heat loss. As a benchmark, consider a flame without heat loss, one that reaches ordinary atmospheric pressure and achieves an ideal state of chemical balance (equilibrium). This is called the *adiabatic flame temperature* (AFT) and can be regarded as the maximum possible temperature that can be attained for a given fuel. Now this AFT depends on the amount of fuel and oxygen present. A mixture of the two is said to be stoichiometric if none of both the fuel and oxygen remains after the reaction. As no extra fuel or oxygen is present for a stoichiometric reaction, this AFT will truly be the ideal maximum flame temperature. It was stated earlier that this is about 2000°C, without any substantial justification. Table 2.2 shows some computed AFT values for typical fuels at stoichiometric conditions burning in air. The prevalent values range from about 1950°C to 1980°C, and these are representative of the majority of hydrocarbon-based fuels including wood and plastics. Notable exceptions occur for acetylene and hydrogen. The results can be explained from the fact that most materials release the same amount of energy in burning 1 g of oxygen. This observation was brought forth by Huggett[6] in recent times, who concluded that 13 kJ/g was a good average value for the energy released per gram of oxygen burned. A stoichiometric concentration is about midway between the LFL and the UFL for most fuels, so since this flammability range is typically 1%–10%, a relatively small amount of fuel burns in proportion to the oxygen in the air. The amount of energy stored in the mixture of air and fuel is based on how much oxygen burns. This portion of oxygen to the mass of the original stoichiometric mixture is approximately a fixed number for all hydrocarbon fuels. Hence, if the energy released per unit mass of oxygen is an inherent constant, the resulting temperature of the mixture will also be constant. This explains the relationship between the AFT for stoichiometric burning in air and the energy release by oxygen burned. Table 2.2 indicates this relationship.

While the AFT is an ideal value, small laminar flames have relatively little heat loss, so they are a good representation of such real temperatures.

TABLE 2.2

Maximum Flame Temperatures (AFT) in Air and Energy Released per Oxygen

Fuel	AFT in Air (Stoichiometric) (°C)	Energy Release in Burning 1 g of Oxygen (kJ)
Acetylene	2500	15.6
Butane	1970	12.7
Ethane	1955	12.7
Hydrogen	2210	15.1
Methane	1950	12.5
Propane	1980	12.9

Source: From various sources.

The propagation of real flames must be near stoichiometric conditions for most fuels (with exceptions of acetylene, carbon monoxide, and hydrogen). Indeed, diffusion flames naturally occur for stoichiometric conditions. So, these small, candle-like flames most often have temperatures in the range of about 2000°C burning in air. As a flame becomes turbulent, its local laminar-like flame will still possess this type of value, but now an average temperature is more relevant, and it will be substantially lower. But chaotic motion of turbulent flow has nothing to do with the fuel, so the turbulent flame temperatures of most hydrocarbon fuels burning in air will be similar.

2.4.3 Turbulent Propagation to Detonation

Once propagation commences in the fuel–air mixtures from the ignition point, flame propagation occurs under laminar conditions at speeds of roughly 0.1–1 m/s. As turbulence occurs, the laminar flame will distort. This "wrinkled" flame will have more surface area and hence more energy, so its speed will increase. The turbulence can occur naturally or as the flame passes over obstacles. These effects cause the flame to accelerate. Exceeding the speed of sound (343 m/s) will cause a shock wave to form ahead of the flame. The shock will feed higher temperature fuel to the flame and accelerate the process to a higher state. A strong shock will result with extremely high velocities of over 2000 m/s. If the speed of the flame is below the speed of sound and no shock wave forms, the process is called a *deflagration*. Above the speed of sound, it is called a *detonation*. Fuel concentration limits needed for detonations have been determined, and these are listed in Table 2.3 with the detonation flame velocities. This detonation process is distinctly different from its subsonic counterpart. However, most explosions attributed to flame propagation in a premixed fuel system are not detonations. They involve burning in a confined space in which the flames begin as laminar and progress to turbulent. The propagations at still fast and will cause pressure rise due to a sudden increase in temperature in the confined space. This can even occur in partially ventilated spaces.

TABLE 2.3

Detonation Limits at Normal Atmospheric Temperature and Pressure

Fuel	Lower Limit (%)	Upper Limit (%)	Detonation Velocity (m/s)
Hydrogen in pure O_2	15	90	2821
Hydrogen in air	18.3	59	—
CO in pure moist O_2	38	90	1264
Propane in pure O_2	3.2	37	2280, 2600
Acetylene in air	4.2	50	—
Acetylene in pure O_2	3.5	92	2716

Source: Lewis, B.J. and von Elbe, G., Combustion, in: *Flames and Explosions of Gases*, 3rd edn., Academic Press, Orlando, FL, 1987, pp. 551–555.

2.5 Smoldering

A flame is combustion in a gas, while smoldering is combustion on a solid surface. Smoldering is a relatively slow combustion process that occurs between oxygen in the air and the solid fuel. Common examples of smoldering are shown in Figure 2.25. The reaction occurs on the solid surface, and oxygen diffuses to the surface. The surface can undergo glowing and charring. In fact, when typical polyurethane foam upholstery material smolders, it will leave a char. But if it burns to form a flame, it will melt. Smoldering is oxidation that leads to a sufficiently high enough temperature. Rusting of iron and the yellowing of paper with age are surface oxidation but are not smoldering or combustion. To class it as combustion, there must be an acceleration of the initial oxidation to a higher-temperature state. While this higher temperature can vary depending on conditions, it could be as low as about 300°C. Again if it can burn your finger, it could be classed as smoldering. Clearly, a glowing oxidizing surface is smoldering, as that is indicative of a temperature in excess of 1000°C.

Upholstered furniture and mattresses initiated by a discarded cigarette are prevalent sources of smoldering fires in homes. Coincidently, the cigarette is classic example of smoldering. As air is drawn through the cigarette, the porous tobacco receives more oxygen and more burns. Smoldering is controlled by the supply of oxygen. However, as it can occur at relatively lower rates of combustion than a flame, it can occur at very low levels of oxygen. Underground fires in abandoned coal mines can smolder for years. On the other hand, every camper knows that blowing on a glowing stick of wood will not only increase its degree of glowing but can spring it into a flame. Airflow is significant to smoldering. Bringing more air to the oxidizing surface causes a higher reaction rate and higher reaction temperature.

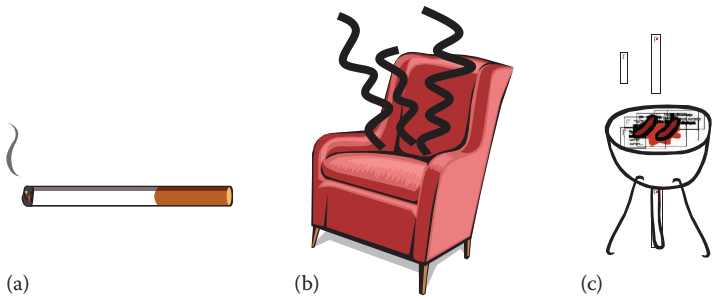

FIGURE 2.25
Common examples of smoldering: (a) cigarettes, (b) upholstered chair foam plastic/cotton fabric system, and (c) charcoal grill.

The fact that smoldering takes place under lower-temperature conditions than a flame does not allow its intermediate species to burn. The incompleteness of the combustion process leads to high levels of carbon monoxide, CO, instead of CO_2. More than 10% of the fuel mass is converted to CO in smoldering carbon-based solids. Smoldering fires that persist for a long time in a confined space as a house can lead to fatal conditions due to CO. Also, many unburned products can build up, creating a potentially flammable atmosphere.

Surprisingly, smoldering has received little study compared to flaming fires. Data can help to illustrate the characteristics of the process and give one an appreciation of its speed. In general, smoldering can occur in porous solid fuels, in combinations of fuels, in impervious solids, and in buried solid fuel waste sites. It requires air, but not much, because the process is so slow. Air can blow in either direction to the smolder front or can be naturally induced to flow due to buoyancy. Smoldering is schematically illustrated in Figure 2.26. The thickness of the smolder region, like a flame reaction zone, increases as the reaction rate decreases. Its thickness and speed depend on the reaction rate. This reaction rate is controlled by the supply of oxygen. In Figure 2.26, air must diffuse through the char from above. If the virgin material is porous, it might induce air to flow upward and enhance this process. The process is complex, but relatively slow, generally of the order of 10^{-3} to 10^{-2} cm/s or 0.6–6 mm/min. This is very slow but potentially deadly because it produces carbon monoxide.

Typical smolder velocities are shown in Figure 2.27 and Table 2.4 for common materials. In Figure 2.27, air was blown through the porous materials, and the smoldering propagation was opposite to the direction of airflow (reverse smolder). It is clearly seen that increasing the air speed increases the smoldering speed. In Table 2.4, airflow was generally parallel to the solid fuel surface, with forward smoldering in the same direction as the flow. For wood-fiber board, the smoldering rates ranged from about 0.8 to 8 mm/min, with the higher levels at high air flow rates of up to 10 m/s (22 mph). Cardboard and cellulosic fabric could smolder at about 5 mm/min in relatively still air.

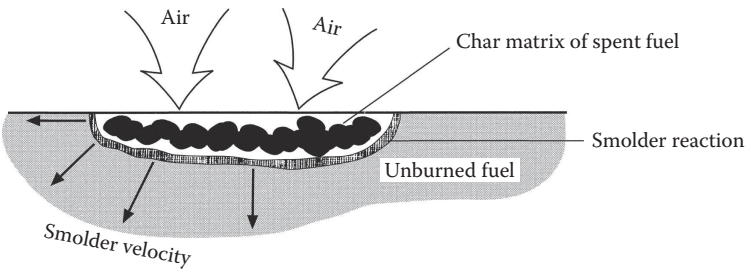

FIGURE 2.26
Schematic of smoldering.

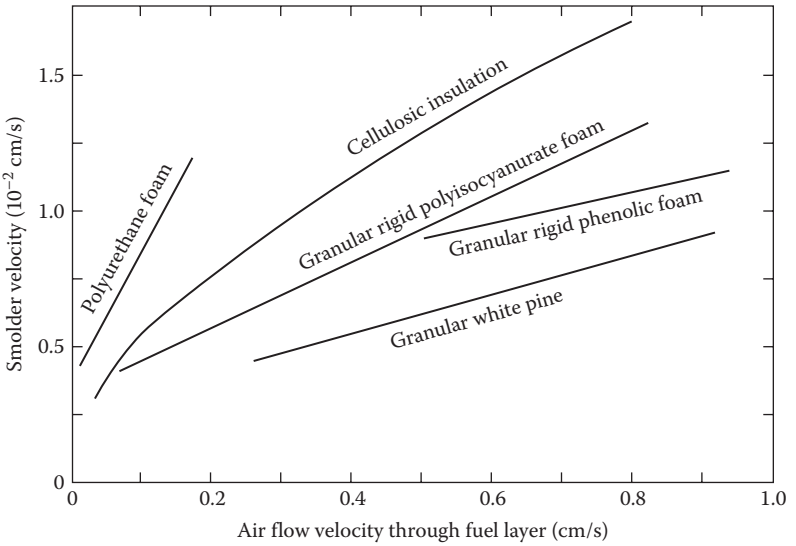

FIGURE 2.27
Reverse smolder velocities depend on airflow velocity. (From Ohlemiller, T.J., Smoldering combustion, Chap. 2–11, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.)

Smoldering can revert to flaming combustion particularly due to an increase in the airflow rate over the fuel. This is implied by the termination of the graphs in Figure 2.27. A transition to flaming can also occur in wood. As the smolder rate increases in a block of wood, the process can revert to flaming after perhaps 1 hour. As the char builds up and the incomplete combustion products move through the hot char, they can reach their AIT and produce a flame. It should be pointed out, however, that as some wood products like fiberboard might be prone to smolder, the smoldering process on wood generally takes some heat supply to be sustained. A confined space to trap the heat could be ideal, once smoldering has begun. Hidden fires generally begin as smoldering.

2.6 Spontaneous Combustion

In the first edition of this book, spontaneous ignition was classed as a form of combustion. This is not precisely true. Once ignition occurs, combustion is in the form of a flame or smoldering. But before that point, we have a chemical reaction that has not yet made the transition to combustion. To reach combustion, we must step through ignition. Ignition can be appreciated by

TABLE 2.4

Typical Smolder Velocities Associated with Fuel Configuration

Fuel	Smolder Configuration	Air Supply Condition	Smolder Velocity (mm/min)
Pressed fiber insulation board, 0.23–0.29 g/cc	1.3 cm thick, horizontal strips, width large compared to thickness	Natural convection/ diffusion	0.78–1.3
"	1.3 cm × 1.3 cm, strips varied angle to vertical	Natural convection/ diffusion	1.6–2.8
"	1.3 cm × 5 cm strips, forward smolder	Forced flow, 20 cm/s, 1500 cm/s	2.1 7.8
"	1.3 cm × 5 cm strips, reverse smolder	Forced flow, 80–700 cm/s	1.7–2.1
Pressed fiberboard (pine or aspen), 0.24 g/cc	1.3 cm × 30 cm sheets, horizontal, forward smolder	Forced flow, 10–18 cm/s	0.42
Cardboard	Vertical rolled cardboard cylinder, downward propagation, dia. 0.19–0.38 cm	Natural convection, diffusion	3.0–5.0
Shredded tobacco	0.8 cm dia. cigarette, horizontal, in open air	Natural convection, diffusion	1.8–3.0
Cellulose fabric + 3% NaCl	Double fabric layer, 0.2 cm thick, horizontal, forward smolder	Forced flow, 10 cm/s	6.0

Source: Ohlemiller, T.J., Smoldering combustion, Chap. 2–11, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

considering a coin being pushed toward the edge of the tabletop. It can be pushed until it is hanging over the edge, yet still on the tabletop. At some small movement, it becomes out of balance and falls to the floor. There it stays until some other force comes along. Ignition is the process of falling. Combustion is sitting on the floor. Before combustion, we have a chemical reaction in balance that is producing an imperceptible amount of energy. It is a producer, *exothermic*, but not a lot at this state. With a little boost to raise its temperature, the reaction will go out of balance and start to produce more energy than it can absorb. Eventually, it will come into balance. The higher-temperature state is combustion. As long as fuel and oxygen are supplied in the amount it needs, it will stay at this state. Of course, cooling it to reduce its temperature can send it spiraling down to extinction: its state before ignition on the table top.

Spontaneous combustion can occur in many media. Figure 2.28 shows some examples. For the fuel–air mixture, if it reaches its AIT by some means it will make the transition to a flame. The process requires some heat

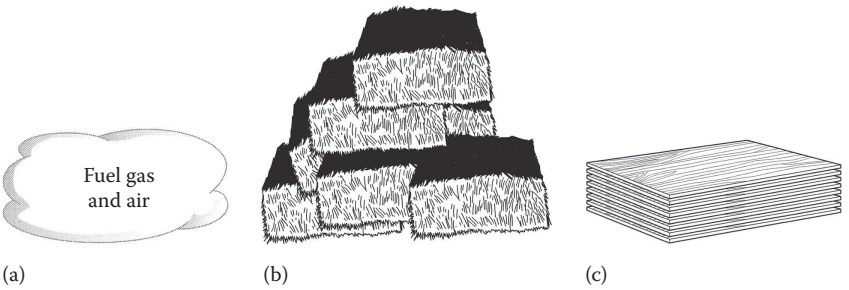

FIGURE 2.28
Examples of fuel arrays prone to spontaneous combustion: (a) mixture of fuel gas and air raised to its autoignition temperature, (b) haystack, biological reactions promoted by moisture, and (c) pile of wood fiberboard or coal waste (slag).

transfer and the availability of oxygen and fuel to be sustained. Haystacks are porous and can allow air to penetrate. If they are wet, they are a breeding ground for microorganisms. These organisms will use oxygen and produce energy. The biological process can give the initial push to raise the temperature of the hay and cascade its chemical oxidation to combustion. Most typically, the first combustion result in porous solid media will be smoldering. But as the smoldering continues, air channels into the core will bring more fresh air to the smoldering and move it to flaming. In the case of porous media, the process will start in the core for a warm environment, or at the source of heat. A telltale sign of the process of spontaneous combustion in pile of material will be the degradation of material in the core of a pile, as this region loses heat least. The bigger the pile, the more difficult it is to lose heat to surface. So, big piles require a lower AIT. The material will not have a unique AIT but will depend on the size and heating conditions. For fuel–air gas mixtures, the AIT is measured in a standard test at a specific mixture volume. Commonly, the vessel is spherical and placed in an oven. For solids or liquids, a wide variation of sizes can result in many AITs. Piles of coal or wood fiberboard can play the same role as the haystack. Each material has its own peculiar chemical characteristic. Any material that releases energy in a chemical reaction is prone to spontaneous ignition. The reaction is usually oxidative, but it can also be simply a decomposition of the material, such as ammonium nitrate. On April 16, 1947, ammonium nitrate stored on the French Liberty ship Grandcamp in the harbor at Texas City, was likely heated by a small fire, ignited, and detonated. About 500 homes were destroyed, and over 3000 people were injured.

Let us consider the spontaneous ignition scenarios of a porous oxidative solid. Three classic scenarios might be considered: (1) a pile standing in air, (2) material on a hot surface, and (3) a hot pile exposed to air. In all cases, the inability of the production of chemical energy to be lost as heat to the surroundings will cause the ignition. For each of these scenarios, for a given

material, there is a critical configuration that will trigger the ignition process. While for a gaseous fuel this process is fast (seconds at most), for a porous solid it can range from minutes to weeks. As oxidation (or decomposition) is occurring, telltale odors might signal the beginning of the process.

The pile in air might consist of linseed oil absorbed on a bundle of cotton rags. Commonly used to clean and restore furniture, this unsaturated oil in combination with the cotton makes a potent source. It has been the cause of many accidental fires, notably the 38-story One Meridian Plaza in Philadelphia (1991). Rags were used to clean the furniture and left near a desk in an office. The resulting fire led to the propagation over several floors with significant structural damage to the building.

The second scenario is a material on a hot surface. A classic old example is wood in contact with a hot steam pipe. This scenario can show the complexity of the process. It can take many years of heating to prompt this ignition. Likely, the wood slowly or intermittently heats and char begins to build up. As the char becomes deeper and more porous, it becomes a good medium for spontaneous combustion. At a critical char thickness and surface temperature, ignition of the char can occur. This is likely to be smoldering at first. The char can smolder away to form a cavity. An increase in airflow and confined space heating within the cavity can then lead to flaming on the wood.

The third scenario is the hot pile. This scenario is characteristic of materials undergoing processing, as with wood resin products or plastics. The formation of plastics involves exothermic reactions. If the reaction is not terminated before the end product is sold, its continuation can lead to spontaneous combustion. It might also be associated with commercial laundries where large hot piles of clothes are removed from a dryer. If the pile cannot lose the heat fast enough, ignition could be triggered.

Although theories exist for spontaneous combustion, they are difficult to apply with high accuracy. An advanced treatise on this subject is given by Bowes, but if one sidesteps his mathematical treatment, he also presents many practical examples.[9] He shows that with the proper material data, a rationale estimation of spontaneous ignition potential can be determined. A vivid excerpt from Bowes[9] describes the range of results for cotton waste soaked with linseed oil.

The amounts of material involved in the initiation of fires can be quite small. For example, Taradoire (1925), investigating the self-ignition of cleaning rags impregnated with painting materials, stated that experience indicated the occurrence of self-ignition in as little as 25 g of rags but, in a series of experiments, found that the best results (sic) were obtained with 75 g of cotton rags impregnated with an equal weight of mixtures of linseed oil, turpentine, and liquid "driers" (containing manganese resinate) and exposed to the air in cylindrical containers made of large-mesh wire gauze (dimensions not stated). Times to ignition generally lie between 1 hour and 6 hour but, for reasons which were not discovered, some samples, which had not ignited within these times and were considered safe, ignited

after several days. Other examples giving an indication of scale have been described by Kissling (1895), who obtained self-heating to ignition, from an initial temperature of 23.5°C, in 50 g of cotton wool soaked with 100 g of linseed oil and by Gamble (1941), who reports two experiments with cotton waste soaked in boiled linseed oil (quantities not stated) and lightly packed into boxes; with the smaller of the two, a cardboard box of dimensions 10 cm × 10 cm × 15 cm, the temperature rose from 21°C to 226°C in 6¼ hour and the cotton was charred.

In short, it demonstrates that not much cotton soaked with linseed oil is needed to achieve ignition, but the time to occur ranged from 1 hour to several days. This propensity to spontaneous combustion can be measured by subjecting a sample of the substance in question to oven air temperatures until the lowest air temperature is found to eventually (in hours or days) cause ignition. The end result can be manifested by smoldering or flaming. As the size of the fuel increases, reducing the ability of heat to be conducted from its center, the critical air temperature needed for ignition decreases. The core temperature at the critical condition will sharply increase to a smoldering or flaming state. So, the combustion starts from within. Additives to the material can enhance this propensity. Bowes[9] reports such experimental results in Table 2.5. As the size of the cube of sawdust increased, a lower oven temperature (AIT) was needed to set off the ignition. The addition of the oil clearly made the sawdust more prone to spontaneous ignition. Such testing and its data can be used to assess the potential for spontaneous ignition in real and larger scenarios. Indeed, in theory, these data can supply needed chemical properties to mathematical models to predict ignition different conditions. But because the real conditions may not be duplicated completely in

TABLE 2.5

Sawdust Cubes, with and without Oil, Exposed to Air Temperatures

Cube Size 2*r* mm	Oil Content (%)	Ignition Temperature (°C)
25.4	0	212
25.4	11.1	208
51	0	185
51	11.1	167
76	0	173
76	11.1	146
152	0	152
152	11.1	116
303	0	135
303	11.1	99
910	0	109
910	11.1	65

Source: Bowes, P.C., *Self-Heating: Evaluating and Controlling the Hazards*, Her Majesty's Stationery Office, London, U.K., 1984.

the test oven, extrapolations are limited in accuracy. Still such results bring some quantitative and rational assessment to the potential of spontaneous ignition. This rationality is especially significant as fires originating due to spontaneous ignition or smoldering are often misdiagnosed. On the other hand, electricity as the cause of fire is likely overprescribed, while spontaneous ignition or smoldering might be at the root instead.

2.7 Summary

Natural fire can be divided into three types of combustion:

1. Diffusion flames
2. Premixed flames
3. Smoldering

Combustion to a flame or smoldering requires an ignition process. Energy must be put into the reactants to achieve a thermally runaway process and a sudden jump in temperature to a combustion state. This jump is caused by the fact that the energy production rate of the reaction depends on temperature. Laminar flames in air can achieve temperatures of about 2000°C and a low of about 1300°C before extinction. Smoldering in air might occur as low as about 300°C. The temperature in a turbulent flame is practically represented by an average much lower than the laminar fluctuating flames in its structure.

The AFTs in air for many hydrocarbons are about 2000°C with some exceptions. This can be explained by the nearly constant energy release of oxygen, about 13 kJ/g.

A diffusion flame has fuel and oxygen on either side of the flame, while in a premixed flame the two are mixed before combustion. A candle flame is representative of a diffusion flame. Soot and other incomplete products of combustion occur on the fuel side of the flame. Smoldering also requires the diffusion of air to the solid fuel.

Smoldering is a slow propagation process at speeds of 0.01 cm/s at most. Laminar premixed flame speeds in air can range from about 20 to 100 cm/s, with turbulent speeds increasing by up to 100 times. Detonation speeds can achieve 2000 m/s.

Spontaneous combustion or autoignition occurs because the fuel undergoes an exothermic reaction (generating chemical energy) that cannot be sufficiently cooled. As a result, the reaction accelerates and leads to either flaming or smoldering combustion. Spontaneous ignition can result by decomposition or by oxidation, as in the drying of linseed oil on cotton. It can take hours or days to develop ignition.

Review Questions

1. What role does temperature play in combustion?
2. Under what circumstances can a premixed flame ignite and propagate?
3. How does a diffusion flame begin?
4. Explain the role of airflow in smoldering.
5. Why might spontaneous ignition take so long?

True or False

1. Autoignition requires a pilot flame.
2. An oxy-acetylene torch is a diffusion flame.
3. A burning pool of gasoline is a diffusion flame.
4. Charring is not likely during smoldering.
5. Plastics cannot smolder.
6. Smoldering can occur in concealed spaces with very little air.
7. A flame must be 10 ft high to be turbulent.
8. Temperature plays a key role in determining if a flame can occur.
9. A canister of raw plastic material with insufficient antioxidants could lead to spontaneous ignition.
10. Most hydrocarbon fuels have about the same flame temperature burning in air.

Activities

1. Conduct and discuss the candle experiments described in this chapter.
2. Measure the velocity of a smoldering process, for example, a cigarette. See how air speed might change the smoldering rate.
3. Put linseed oil soaked (not too wet) cotton rags in a cardboard box about 1 ft^3. Place in a safe place for doing fire tests and let sit for several hours. Explain the results. Measure the center temperature if possible.
4. Compare the different flames produced by a Bunsen burner by regulating the air vents. Can you blow the flame off by increasing the flow too high? Can the premixed flame, with the vents open, be extinguished as the fuel flow rate is decreased? With the vents closed, as you increase the fuel flow rate does the flame height level out?

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3

Heat Transfer

Learning Objectives

Upon completion of this chapter, you should be able to

- Describe the difference between energy and heat
- Explain conduction, convection, and radiation heat transfer
- Describe the concept of heat flux and its significance to hazards from fire
- Perform simple computations in heat transfer

3.1 Introduction

Although chemistry and fluid mechanics are important in the study of fire, we can forgo their study for elementary quantitative purposes here. Fluid flow is important to know how air enters a flame and how smoke travels in a building. Mostly, this flow is due to buoyancy created by the fire and hot smoke itself. Wind is important for fires in the open, as in forest fires and conflagrations. In our study of fire plumes (Chapter 7) and compartment fires (Chapter 9), these aspects of fluid flow will be addressed. Of course, chemistry is important, as it is the basis of combustion. In the previous chapter, we have learned that chemical reaction takes place relatively fast, and therefore, as the fuel and oxygen burn, the reaction region is very thin. Often in even sophisticated analysis of flames, the actual chemical dynamics and reaction mechanisms can be ignored. An assumption for a flame of having zero thickness can suffice, and there the fuel and oxygen immediately become products of combustion. However, the importance of heat transfer cannot be avoided if we are to develop the ability to make

quantitative analyses. Heat transfer causes the solid and liquid fuels to vaporize to produce the gaseous fuel for the flame. Heat transfer is responsible for making the fire move over surfaces and through the forest. Indeed, it is the dominant factor in determining the fate of fire growth and the damage it can produce. Therefore, for fire we must first develop some understanding and computational ability in heat transfer before we can appreciate aspects of fire behavior.

3.2 Definitions and Concepts

Before we begin the study of heat transfer, some concepts and definitions have to be introduced. First, the concept of energy must be introduced. The study of energy is rooted in the subject of thermodynamics, a very logical science that carefully defines energy, heat, temperature, and other properties. As with fluid flow, heat transfer, and chemistry, thermodynamics is at least a semester course in itself. Therefore, only the essential aspects of thermodynamics will be considered.

All matter has energy (E) and mass (m); these are the essential properties of matter. In the famous equation of Einstein, $E = mc^2$, mass and energy are related and can be converted into each other. These, of course, are nuclear reactions that play no role in fire. The speed of light (c) is so large that the conversion of mass to energy is enormous. These conversions do not apply here, and for a fixed piece of matter its energy and mass cannot change. This fact is founded in the conservation laws of mass and energy. The equation of Einstein that applies only in a nuclear reaction simply allows the interchange of these two quantities. Indeed, atomic physicists do not distinguish between the two. The conservation of mass and energy cannot be proven; it is taken as a general truth. Moreover, mass and energy cannot be directly defined; they are conceptual. Yet, we can sense and measure their effects. This is a little deep, so we will try to get a bit more tangible.

As all matter possesses energy, it can take many forms. Some we can readily recognize. The other forms of energy are discerned indirectly from the conservation of the energy. By the way, this conservation law is called the First Law of Thermodynamics. Let us recognize some of the forms of energy. When we lift a weight over a distance, the required force times the distance moved is called work. In the SI system of units, work is force (N for Newton) times distance (m, meter); or its unit of measure is N-m. An alias for 1 N-m is a joule, J: a common unit of energy. (In the English system, J is related to BTU.) The industrial revolution allowed us to burn coal, heat a boiler to create steam, and move a piston to produce work. In that process, several other forms of energy show up. Chemical energy results from the

oxidation of coal to products of combustion. Heat transfer brings energy to the boiler. The motion of the piston manifests as kinetic energy and is then converted into work. Energy is a state of matter from which we might extract work or obtain heat. If there is no motion and no chemical reaction, does that mean that no more energy exists in the original matter from which work and heat were extracted? No, there is an intrinsic energy left and persists as long as the atoms are in motion. You might say this is the kinetic energy of the moving atomic particles. This is called *thermal energy* (or more thermodynamically correct, *internal energy*).

Thermal (or internal) energy is a property of matter directly associated with the concept of temperature. Something that is "hot" has a relatively higher internal energy and temperature compared to that which is "cold." The level of hot and cold needs to be quantified, and various temperature metrics have been developed to do this. The scales used to measure temperature are arbitrary and have been established by convenience as well as by science. The common four scales and their relationship are illustrated in Figure 3.1 (see Table 1.6). They have been historically based on the freezing and boiling points of water. The "distance" or temperature measure between them has been arbitrarily assigned +32 and 212 for freezing and boiling on the Fahrenheit scale and 0 and 100 on the Celsius (or centigrade) scale. One might begin to see why the Celsius scale is preferred. In addition, there are two modifications of these scales. These are the absolute scales that set zero temperature at zero internal energy. They are expressed in degrees Rankine (°R) for the scale in increments of Fahrenheit degrees and in Kelvin (K) associated with the Celsius increments. Zero kelvin is the same as –273°C, and the increments on the two scales are the same. The absolute temperature scale will be important in heat transfer, as formulas for radiation use this scale. At the absolute zero state, the molecular

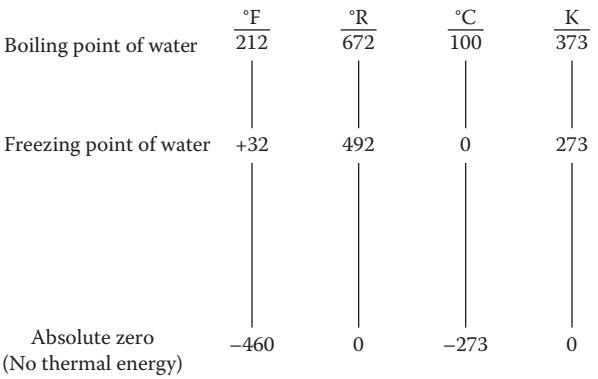

FIGURE 3.1
Temperature scales.

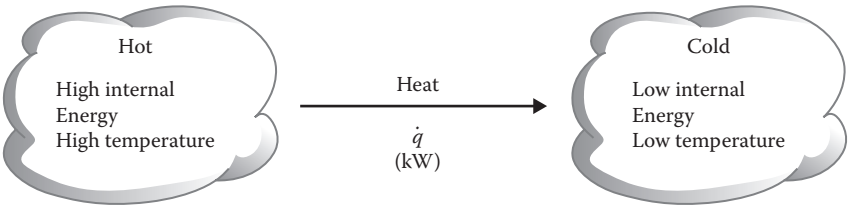

FIGURE 3.2
Heat transfer as energy exchange between hot and cold.

mechanical activity ceases. Temperature is a direct measure of this activity, and at this "absolute zero point," it is the lowest possible temperature for matter.

Heat is defined as thermal energy in motion that travels from a "hot" to a "cold" region. This process is symbolically illustrated in Figure 3.2. There are two laws that govern this heat transfer: one deals with the energy travel within matter and the other can travel in the absence of matter (vacuum).

The symbol q represents heat (while Q represents chemical energy in this chapter). Both are measured in joules (J). It takes 4.182 J (or 1 cal) to raise 1 gram (g) of water 1°C (see Tables 1.5 and 1.7 for alternative units and notation). The rate of heat flow or the rate of chemical energy generated (transformed) is commonly given in J/s or its alias, watt, W. For example, if we transfer by heat 4.182 J to 1 g of liquid water, its internal energy will increase by 4.182 J and its temperature by 1°C. If it takes 1 second to accomplish this, we have 4.182 J/s or 4.182 W of heat flow rate. If that transfer rate continues for 25 seconds, the temperature of water will increase by 25°C. Hopefully, before the end of this book, you will relate to fire in terms of its W output in the same way you relate to ratings for a light bulb, furnace, or toaster. It is common to relate the size of fire in terms of kW.

An important quantity in heat transfer is heat flux. It is defined as the flow rate of heat per unit area it passes through. More precisely, imagine heat flow rate depicted by an ensemble of arrows in the direction of everywhere it is flowing. The area through which one arrow flows is perpendicular to this arrow. For a single arrow, consider its flow area shrinking to a point. The ratio of that heat flow rate associated with the arrow and the small area reduced to a point gives the heat flux. Its symbol is given as $\dot{q}''$, and its units are typically kW/m^2. Heat flux is a point function, while heat flow rate applies to sum of all the heat flux passing through the area of the heat flow. In heat transfer, the heat flux will vary over a region in general. Close to a hot source, we would experience a higher heat flux than farther away. Touching a hot plate would give a higher heat flux than touching its insulated edge. It is the heat flux that we feel by the Sun on a cold day. It is the heat flux

that makes objects burn and cause damage in fire. It is the most important quantity that expresses the hazard of fire.

We will examine the forms of heat transfer and how they apply to fire. The key parameter will be heat flux.

3.3 Forms of Heat Transfer

The "laws" of conduction and radiation govern heat transfer. These "laws" are not as perfect as the Conservation Laws of Mass and Energy; they are just very good approximations. In the early 1800s, Joseph Fourier formulated the law of heat conduction. It described the rate of heat flow through matter as directly proportional to temperature difference divided by the distance separating those temperatures in the substance. He was a scientist working in Napoleon's army on the cooling of cannon barrels. War motivates discoveries. It took nearly 100 years later to discover the heat transfer relationship for radiation. Formulated in the early 1900s, Max Planck's quantum theory led to a theoretical basis for radiation heat transfer. Such radiation moves at the speed of light in a vacuum and is very different from the way conduction moves.

Convection is another category of heat transfer but it does not require a separate "law" to predict it, as it is a subset of conduction. It applies specifically to conduction in a moving fluid. Figure 3.3 illustrates these forms of heat transfer in a fire situation of a flame against a wall. Conduction occurs through the wall, convection occurs at the wall–flame or smoke interface, and radiation can be felt at a distance and to the wall. Also, radiation comes from the flame, smoke, and the hot wall.

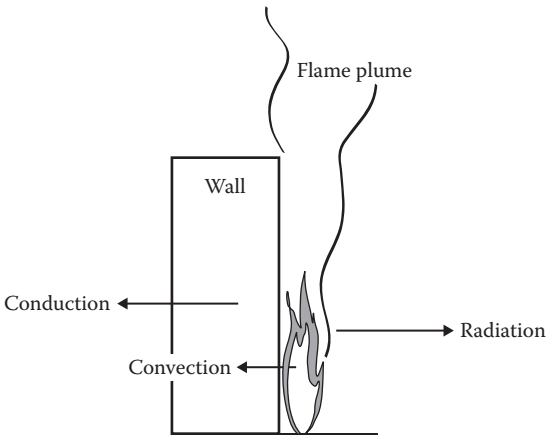

FIGURE 3.3
Examples of heat transfer in fire.

3.3.1 Conduction

3.3.1.1 Steady

The simplest representation of the law of conduction is given as follows in steady form (unchanging with time) for the flow rate of heat through a wall. This is illustrated in Figure 3.4. The equation is given as

$$\dot{q} = \frac{kA(T_2 - T_1)}{l} \tag{3.1}$$

where
k is the thermal conductivity
A is the area through which the heat is transferred
T_2 and T_1 are the respective temperatures of the wall faces
l is the wall thickness

This equation says that the rate of heat flow (e.g., kJ/s or kW) between two temperatures, T_1 and T_2, in a solid is proportional to a property of the solid known as thermal conductivity (k). Also, the larger the flow area through which the heat is conducted, the greater is the flow rate, $\dot{q}$. This is analogous to the increase in the rate of water flowing through a pipe as its diameter is increased. It should be remarked that this relationship for conduction is analogous to the flow rate of electrons (current) in a metal wire as being controlled by the voltage difference and the electrical resistance of the wire.

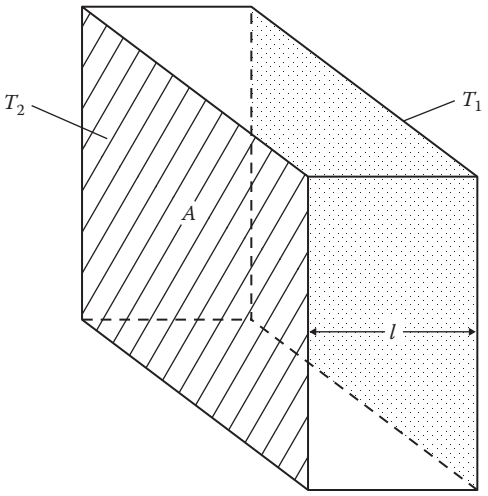

FIGURE 3.4
Heat conduction through a wall.

A resistance factor is similarly used for heat conduction. The commonly used *R*-value for home siding insulation is the reciprocal of kA/l. This *R*-value is called thermal resistance as an analogy to electrical resistance where $\dot{q}$ takes on the role of current flow rate and temperature takes the role of voltage. Let us consider an example.

Example 3.1

Find the heat flow rate per unit area through a wall of polyurethane foam, 0.05 m thick (l), across a temperature difference of 40°C–20°C. Note that heat flow rate per unit area is called heat flux (denoted by $\dot{q}''$):

$$\dot{q}'' = \frac{\dot{q}}{A} = \frac{(0.034 \text{ W/m-K})(40 - 20)^\circ\text{C}}{0.05 \text{ m}} = 13.6 \text{ W/m}^2$$

or 0.013 kW/m^2

Consider the same conditions of temperature, thickness, and area, except the solid is now steel. Here, k (from Table 3.1) is 45.8 W/m-K. Note that whether we use K or °C in the thermal conductivity term (or for the temperature in the formula), there is no change. This is so because

TABLE 3.1

Table of Thermal Properties

Material	Thermal Conductivity (k) (W/m-K)	Specific Heat (c) (kJ/kg-K)	Density (ρ) (kg/m^3)	Thermal Diffusivity (α) (m^2/s)	Thermal Inertia ($k\rho c$) (kW^2-s/m^4-K^2)
Copper	387	0.380	8940	1.14×10^{-4}	1300.0
Steel (mild)	45.8	0.460	7850	1.26×10^{-5}	160.0
Brick (common)	0.69	0.840	1600	5.2×10^{-7}	0.93
Concrete	0.8–1.4	0.880	~2000	5.7×10^{-7}	2.0
Glass (plate)	0.76	0.840	2700	3.3×10^{-7}	1.7
Gypsum plaster	0.48	0.840	1440	4.1×10^{-7}	0.58
PMMA	0.19	1.420	1190	1.1×10^{-7}	0.32
Oak	0.17	2.380	800	8.9×10^{-8}	0.32
Yellow pine	0.14	2.850	640	8.3×10^{-8}	0.25
Asbestos	0.15	1.050	577	2.5×10^{-7}	0.091
Fiber insulating board	0.041	2.090	229	8.6×10^{-8}	0.020
Polyurethane foam	0.034	1.400	20	1.2×10^{-6}	9.5×10^{-4}
Air	0.026	1.040	1.1	2.2×10^{-5}	3.0×10^{-5}

Source: Drysdale, D., *An Introduction to Fire Dynamics*, Wiley, New York, 1985, p. 36.

we are concerned with temperature differences and the degree in the numerator and denominator cancels out. The calculation for this case is

$$\dot{q}'' = \frac{(45.8 \text{ W/m-K})(20°\text{C})}{(0.05 \text{ m})} = 18,320 \text{ W/m}^2$$

or

$$\dot{q}'' = 18.3 \text{ kW/m}^2$$

Thus, we see the ability of heat flow to conduct through steel is much greater than through an insulator-like polyurethane.

Under fire conditions, heat conduction can play a role in propagating the fire. Fires have been known to propagate on ships due to direct heat conduction through the steel floors and bulkheads. Substances can ignite due to conduction if they are in contact with a very hot body. Also, corners will ignite before edges, which in turn will ignite before a flat surface of the same material for the same heat flux. In those geometries, the one with the least mass will heat more quickly. In general, the transfer of heat is more complex than we have depicted it by Equation 3.1. Layers of different materials, their shape, and the time for thermal penetration all add to the complexity and must be considered for an accurate prediction of the temperature.

In general, heat transfer is unsteady, and it takes some time for the heat to penetrate through the substance, raising its temperature as the heat reaches a new depth. A rough estimate of how long it will take the temperature to be effectively felt at a given depth can be made. If the surface of a material suddenly has an increase in temperature, the time for the temperature to increase at a distance (x) within the material is proportional to x^2/α.

3.3.1.2 Thermal Penetration Time

The thermal penetration time for a 1% increase in temperature rise at x is approximately $x^2/12\alpha$ or to reach 50% of the increase is approximately x^2/α where $\alpha = k/\rho c$, thermal diffusivity, ρ is the density, and c is the specific heat.

The thermal diffusivity is a measure of how fast it takes a thermal effect to be felt within a still cup of coffee. The motion of heat in the coffee is analogous to the motion of dissolved sugar from a solid lump at the bottom of the cup. This phenomenon is known as *diffusion* of the sugar through the coffee. The molecules of sugar and coffee liquid are intermingling, and the concentration of sugar is rising throughout. The heat conduction propagation within the material is due to *thermal diffusion* or the diffusion of heat that excites neighboring molecules. As the internal energy of the molecules

is raised by atomic vibrations from their hotter neighbors, temperature increases and heat is propagated, somewhat like a wave effect.

How long would it take the back wall in the polyurethane Example 3.1 to realize that heat has been applied to the front wall? The thermal diffusivity can be found from Table 3.1:

$$\text{Time (1\%)} = \frac{(0.05\ \text{m})^2}{(12\ (1.2 \times 10^{-6}\ \text{m}^2/\text{s}))} = 174\ \text{s}$$

In contrast, the steel wall has a (1%) penetration time of about 16.4 seconds. Following this transient propagation, steady conduction through the wall will take place after this penetration time. Then Equation 3.1 can be applied. All of these facets must be considered in analyzing heat conduction.

In the past, exact sophisticated mathematical solutions were rendered for conduction problems. Today, modern computers are capable of doing the same and for more complex problems. However, in the end, the material properties have to be known, and conditions in the surroundings of the conducting material need to be known. If that material is a solid in a hot fluid such as air, the conduction between the air and the material needs to be computed. If the air is moving, this conduction will be affected by the flow.

3.3.2 Convection

In a moving fluid, the heat transfer from the fluid to a solid surface is called convection, but the governing law is still that of conduction. However, the temperature difference and distance traversed near the surface are not readily measured or derived from pure conduction considerations. For example, as hot air flows over frozen water, the heat transfer by conduction at the ice surface depends on the temperature difference near the surface, ΔT. By the law of conduction, the heat transfer at the ice surface from the air as illustrated in Figure 3.5 is still given by Equation 3.1:

$$\dot{q} = kA \cdot \frac{\Delta T}{\Delta l}$$

where Δl is the distance between the temperatures corresponding to ΔT. The heat flux to the wall is

$$\dot{q}'' = \frac{\dot{q}}{A} = k\frac{\Delta T}{\Delta l}$$

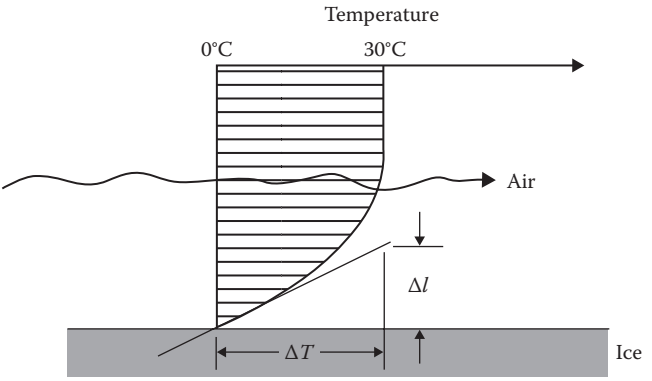

FIGURE 3.5
Convective heat transfer example.

The ratio $\Delta T/\Delta l$ must be known *just* at the surface to give a value for this heat flux. As the temperature in the hot air varies sharply as the air gets closer to the surface, only very detailed temperature measurements or complex computations (calculus) can resolve this ratio. Alternatively, the equation is rearranged in terms of the known temperature difference between the hot air stream and the ice, as

$$\dot{q}'' = \left(\frac{k}{\Delta l}\right)(T_2 - T_1)$$

where
T_2 is the air stream temperature (e.g., 30°C)
T_1 is the surface temperature (e.g., 0°C)

The flow speed of the air will affect the distance Δl; the higher the flow speed, the more Δl will be reduced. In physical terms, here Δl is a fraction of the thickness of the air region between 30°C and 0°C. That region is called a *boundary layer* in fluid mechanics. The quantity $(k/\Delta l)$ is now lumped into one parameter that is defined as the convective *heat transfer coefficient* given by the symbol, h. It depends on the air properties as well as the flow speed. Therefore, the equation for a flowing fluid that gives the heat flux at the surface is given as

$$\dot{q}'' = h(T_2 - T_1) \tag{3.2}$$

The heat transfer coefficient provides a simple means to evaluate the convective heat flux in a fluid stream flowing over a surface across which the temperatures are known. It is too complicated for us to explain all the

TABLE 3.2

Typical Values for Convective Coefficients, h

Fluid Condition	h (W/m²-°C)
Buoyant turbulent flows in air	5–10
Laminar match flame	~30
Turbulent liquid pool fire surface	~20
Fire plume impinging on a ceiling	5–50
2 m/s wind speed in air	~10
35 m/s wind speed in air	~75

methods for determining h. This is the subject of a convective heat transfer course and involves the prediction of h through measurements or calculations of the flow over the particular surface.

For fire processes, we do not need much information to make most estimates for h, as the flow field is primarily natural convection driven by buoyancy. Table 3.2 gives typical values for h. Fire conditions do not significantly change the values given for air as suggested in Table 3.2. So, if we know the temperatures of the flow stream and the flow surface, we can estimate the heat transfer coefficient from Table 3.2 and use Equation 3.2 to estimate the convective heat flux to or from the surface.

Let us consider a fire example.

Example 3.2

Find the convective heat flux from a turbulent flame to a cold wall at 20°C. Estimate the h value from Table 3.2 for free convection (a buoyant flow that is indicative of a flame) as about 5–10 W/m²-°C. Let us select 5 for illustrative purposes here. The maximum time-averaged flame temperature is given as approximately 800°C.

$$\begin{aligned} q''' &= (5\ \text{W/m}^2\text{-°C})\ (800 - 20)\text{°C} \\ &= 3900\ \text{W/m}^2 \\ &= 3.9\ \text{W/m}^2 \end{aligned}$$

Had we used 10 W/m²-°C for h instead, our answer would be double. This range of 5–10 kW/m² is representative of most turbulent fire conditions. The convection heat flux to a burning (vaporizing) surface will be slightly less because the flow of fuel gases will push the hot flame away from the surface, increasing Δl (see Figure 3.5). Also, for laminar flames, the flame will be closer to the surface, which corresponds to a smaller Δl. For this reason, small laminar flames have a higher convective heat flux than turbulent flames. Near the surface of a pool fire, the flow will be laminar near its edge and turbulent above.

For the range of convective fire conditions, Table 3.2 suggests that for laminar flames, the convective coefficient is about 30 W/m²-K. This is an estimate and decreases from the place where the flow begins on the surface. That is where the flame is closest. Near the beginning point, this value could be double. Also for laminar flames, the flame will be thin, and its temperature could be as high as 2000°C. A computation of the convective laminar flame heat flux from Equation 3.2 would give heat fluxes ranging from about 60 to 120 kW/m². These values are high compared to the more general fire conditions where turbulent flow prevails. In turbulent flow, the flame is thicker and spread out due to the fluid fluctuations and mixing in the flow. The temperature at any fixed point in the reaction region varies rapidly due to these fluctuations. Measurements show that this time-average temperature is about 800°C–1000°C for most fires but could achieve as much as 1200°C for very large flames. From Table 3.2, the turbulent convective coefficient is about 5–10 W/m²-K for buoyant flames along walls. This gives a peak convective heat flux of only 10 kW/m² for turbulent fire conditions. Even in the higher velocity impingement region from a turbulent flame plume at a ceiling, this value might only achieve about 50 kW/m² just at the region of impingement. We see that the laminar flame is more powerful than its turbulent counterpart in convective heating. The impact on fire hazard is mitigated as laminar flames quickly become turbulent after lengths of about 0.3 m (1 ft). But the turbulent convective heat fluxes alone are not generally sufficient to sustain fire. We need something else. This comes from the other way heat can be transferred—*radiation*.

3.3.3 Radiation

Planck established the theoretical basis for explaining radiation heat transfer. All radiation is electromagnetic energy consisting of both electric and magnetic fields. This is distinctly different from the intimate molecular transmission nature of conduction. These radiation rays have both a frequency and a speed (the speed of light in a vacuum, c = 29,979,245,800 cm/s) and can traverse within materials and through a vacuum of nothing. The frequency (f) range determines the descriptive name or phenomena we associate with the radiation. For example, high-frequency (alternatively low wavelength, $\lambda = c/f$) radiation phenomena, in descending order, include cosmic rays, gamma rays, and x-rays reaching into ultraviolet, which borders visible light (a form of radiation). In decreasing order from visible light, we move to infrared and then radio waves. Thermal radiation is mostly felt across the infrared and somewhat into the visible. However, it is generated over the entire frequency spectrum by any piece of matter having a finite temperature (on the absolute scale). Objects having temperatures of about 1000°C can appear bright red; we "see" the thermal radiation within the frequency or wavelength range sensitive to our eye. At about 3000°C, they appear white. The use of an infrared camera extends our ability to *see* lower temperatures.

Night vision cameras do this, making humans visible on a dark night. A characteristic of smoke is that its transmission of radiation (light) decreases with increasing wavelength. Such cameras, operating at the higher wavelength (infrared), enable one to "see through" smoke until its concentration gets too high to block the light.

Radiation originates in different ways. Radio waves can be electronically developed for broadcasting. For example, at 100 MHz (Megahertz) or 100 million cycles per second on our FM dial, we might find station WFIR. Thermal radiation originates solely due to temperature. All matter having a temperature above absolute zero emits radiation. This radiation has a frequency range and can be predicted from Planck's theory; however, we will not examine radiation in how it varies and is affected by its frequency. Rather than examining how thermal radiation spans the radio dial we simply examine its overall output. The maximum possible output of radiation due to temperature is given by Planck and is expressed in terms of heat flux as

$$\dot{q}'' = \sigma T^4 \tag{3.3}$$

where

T is the object's temperature expressed in kelvin (K)

σ is called the Stefan–Boltzmann constant given as 5.67×10^{-11} kW/m^2-K^4

This formula applies to a perfect radiator or *blackbody*. It gives the maximum radiation emitted at a given temperature.

Objects do not necessarily radiate at the maximum output given by Equation 3.3. Surface effects and absorbing effects reduce this output. The property that gives the fraction of real output to the maximum value is called *emissivity*, symbolized by the Greek letter ε. For solid and liquid surfaces, ε is typically 0.8 ± 0.2 for fire radiation applications. This means that about 80% of the radiation given by Equation 3.3 is emitted from such an object. That radiation leaves the surface now as heat and moves to objects of lower temperature. Here, we are considering a surface that is *opaque* or nontransmitting. No radiation can pass through an opaque surface. Objects that are not opaque can have radiation pass through them, and radiation can be emitted and absorbed throughout its depth at all of the object's temperatures. A window glazing does this for the low wavelength radiation contained in the Sun's radiation but does not allow the longer wavelength radiation emitted by the lower-temperature objects in a room to be transmitted out. Radiation emitted from a transparent object emits radiation from within as well as its surface.

Gases, smoke, and flames can be transparent to radiation. An effective emissivity of a uniform temperature transparent object such as a flame depends on the thickness of the flame. Flames radiate from gases in the form of discrete pockets of radiation in the wavelength spectrum (fuels and combustion products comprise these gases). In addition, soot particles radiate over the

entire radiation wavelength spectrum. For turbulent flames, the main source of radiation is the soot. A single soot particle nearly follows Equation 3.3 for the radiation emitted from its surface. But for a collection of soot particles suspended in smoke or flame, each particle radiates and intercepts according to how much is there. This means that in smoke or flame, the concentration of soot is important. The amount of radiation that finally reaches the edge of the smoke or flame from this internal emission must also depend on its overall depth. Consequently, it might be approximated that the effective emissivity of this smoke or flame can be estimated from the formula

$$\varepsilon = 1 - \exp(-\kappa l) \tag{3.4}$$

where
κ is the absorption coefficient of the smoke or flame
l is its thickness

The absorption coefficient is a property of the flame and is a measure of how easy it is for the radiation to penetrate the flame. It depends on the nature of the soot and its concentration for the most part. For example, x-rays have a relatively low absorption coefficient for body tissue, implying easy penetration of the x-rays to see organs. For turbulent flames, κ typically ranges from 0.1 to 1.0 m^{-1}. For common fuel flames having a thickness of 1–2 m or more, their ε would be nearly 1. This means that such flames emit the maximum radiative output as an ideal emitter in Equation 3.3. But for very large fires, cold soot on its edges can actually obscure the flame and reduce the radiant heat flux to the surroundings from the high-temperature luminous regions of the flame. This situation is contrary to the notion that large fires emit more radiant heat flux at their surface than smaller fires. However, as they are bigger, they will have more surface area, and more radiation will be sent to the surroundings.

Let us consider a calculation for the incident radiant heat flux to a remote target object caused by a fire or a hot surface such as depicted in Figure 3.6. We consider two distinct problems here: (1) radiation from the hot surface and (2) radiation from the flame alone. In both cases, the radiant heat flux that is received at a target a distance, c, away will be reduced from that emitted by T_2. The fraction of energy reduced is called the configuration or *view factor*, designated by F_{12}. It represents the fraction of rays that can be seen from the target relative to the emitting object compared to the full field of view in the direction of the object (see Figure 3.7). Consider your eye the target. View an object in the room. The fraction that object subsumes in your 180° field of view is the view factor. If the emitting object were a hemisphere to a target at the center, the fraction would be 1, as all of the possible rays leaving the target intercept the hemispherical source. Another interpretation of F_{12} is that it is the fraction of radiant heat leaving the source that strikes the object. F_{12} depends on distance, c; the size of the source object $a \times b$; and the surface orientation of both object and target.

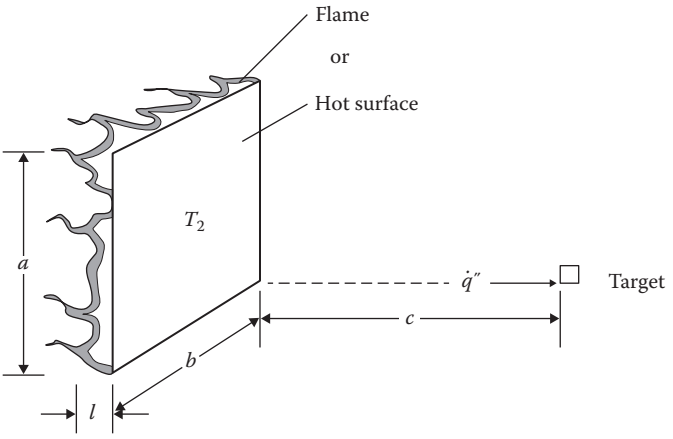

FIGURE 3.6
Radiation to a target from a hot surface or flame at a temperature T_2.

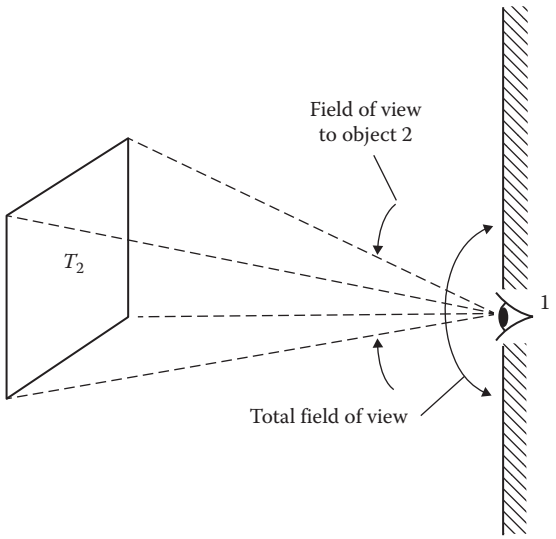

FIGURE 3.7
F_{12} represents the fraction object 2 makes in the total field of view from 1.

For the arrangement depicted in Figure 3.6, F_{12} can be found from the chart given in Figure 3.8. In the chart, $x = a/c$ and $y = b/c$. In that figure, the target is located on a line that is normal to the bottom corner of the source, represented as a flat surface. The surface of the source is also normal to this line. If the face of the target is turned by 90°, it could no longer see the target, and

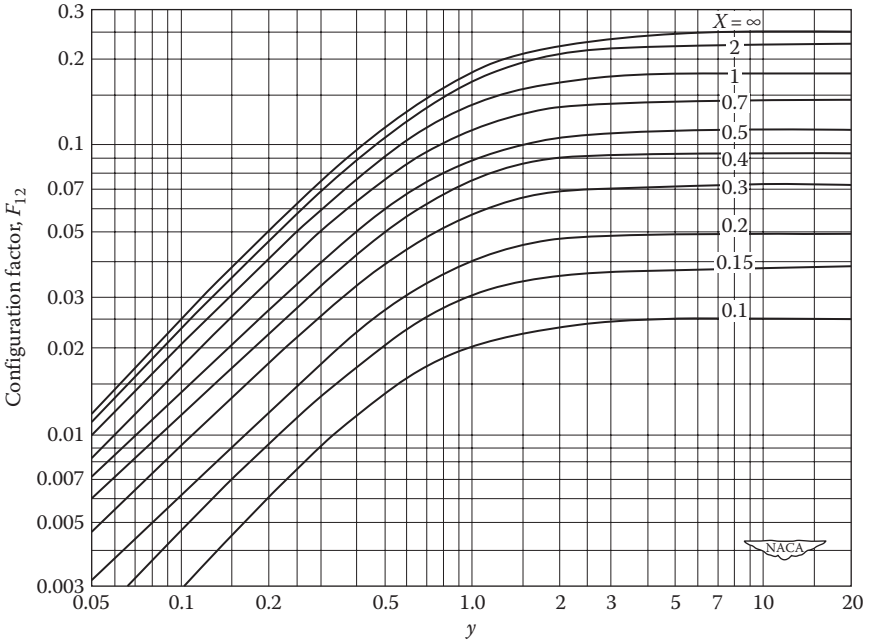

FIGURE 3.8
Configuration factor, F_{12}. (From Hamilton, D.C. and Morgan, W.R., Radiant-interchange configuration factors, NACA Tech. Note 2836, Washington, DC, December 1952, p. 78.)

F_{12} would be equal zero. Typical heat transfer references contain many charts for different configurations.

The heat flux received by the target object is given as

$$\dot{q}'' = \varepsilon\sigma T_2^4 F_{12} \tag{3.5}$$

Let us consider an example based on Figure 3.6.

Example 3.3

Find the heat flux due to radiation from a wood fuel flame 1 m tall (*a*), 0.5 m wide (*b*), and 0.5 m thick (*l*) at a distance 3 m away (*c*). κ is 0.8 m^{-1} and the temperature is assumed to be 800°C. (It is very difficult to make precise radiation calculations because the fuel flame properties are approximate and these data are scarce. Nevertheless, we can make estimations.) First, the temperature must be converted to the absolute scale by adding 273:

$$T_2 = 800°C + 273°C = 1073\ K$$

The emissivity of the flame is then computed from Equation 3.4:

$$\varepsilon = 1 - e^{-\kappa l} = 1 - \exp[-(0.8\ m^{-1})(0.5\ m)] = 0.33$$

To determine F_{12}, we need to compute the x and y of Figure 3.8 relative to Figure 3.6:

$$x = a/c = 1/3 = 0.333$$

$$y = b/c = 0.5/3 = 0.167$$

From Figure 3.8, locating the x-curve approximately, as there is none for 0.333, and then the horizontal axis y value, $F_{12} = 0.017$, is estimated from the vertical axis. Now Equation 3.5 is used to compute the radiant heat flux received at the target:

$$\dot{q}'' = \varepsilon\sigma T_2^4 F_{12} = (0.33)(5.67\times10^{-11}\,\text{kW/m}^2\text{-K}^4)(1073\text{ K})^4(0.017)$$
$$= 0.42\text{ kW/m}^2$$

What if the source in this example were four times as large with the target on the center axis? We have the same problem four times and the heat flux received would be 4 × 0.42, or 1.68 kW/m^2. This is starting to feel like that from the Sun on a clear day, as that value is at most 1 kW/m^2.

Go back to the original example and compute it again for c = 1 m to see the difference. In doing so, you would get F_{12} = 0.09 and 2.2 kW/m^2, or about five times as much. Some might recall that it is commonly said that "radiation falls off as the distance squared." From 1 to 3 m, this common rule would say it falls off by 1/9 or would be reduced to 2.2/9 or 0.24 kW/m^2. From our first computation, the value at 3 m should be 0.42 kW/m^2. So, this common "rule" is approximate and applies only for the ideal case of radiation coming from the center point to a distance on a spherical shell. If the radius of the spherical shell is c, its surface area is $4\pi c^2$. We will see in moment that this ideal case can give us an alternative way of estimating flame radiation to a target.

The computation of radiant heat flux to a target is very important to assess potential damage and the possibility of a remote ignition from a fire. Since the computation depends on flame shape and properties, it can be tedious if not impractical. Fortunately, there is an alternative formula for a discrete fire that is accurate as long as it is applied more than two flame diameters from the center of the flame, that is, $c > 2l$ (see Figure 3.9). The formula is

$$\dot{q}'' = \frac{X_r\dot{Q}}{4\pi c^2} \tag{3.6}$$

where

$\dot{Q}$ is the combustion energy release rate of fire (kW)

X_r is the fraction of energy radiated relative to the total energy released

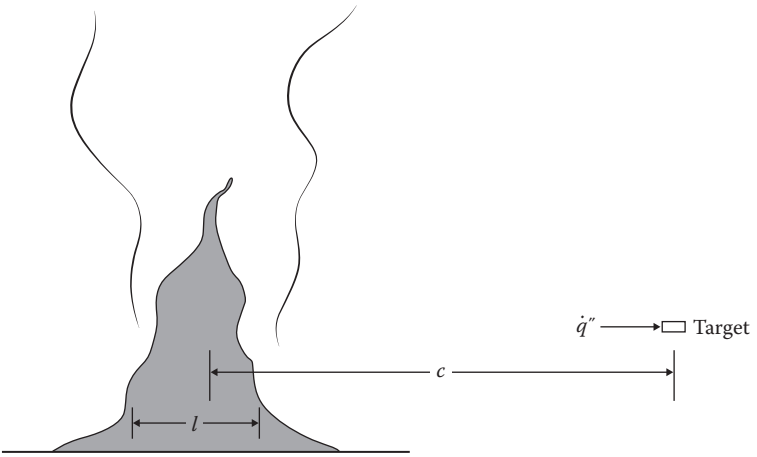

FIGURE 3.9
Radiation heat flux to a target from a point source representation of a flame.

X_r is not necessarily a constant for a given fuel and generally varies from about 0.15 to 0.60 for low sooting fuels such as methane and high sooting flames, such as polystyrene, respectively. Table 3.3 gives some general guidance for some fuels, and Table 3.4 gives some more specific values according to the diameter of the fire. In particular, the data for gasoline clearly show that the radiative fraction drops as the diameter increases. For a 1 m diameter gasoline pool, the radiation fraction is 0.60, but for a 10 m fire, the fraction is 0.10. Figure 3.10 more clearly shows this trend for a number of fuels. The drop off is due to the cold soot swirling around the core of the luminous flame for these large fires, as illustrated in Figure 3.11. The soot blocks the radiation and traps it with the large turbulent flame.

Equation 3.6 is based on uniform radiant emission from a "point source" approximating a flame. All of the radiant energy released, $X_r\dot{Q}$, is uniformly received over a sphere of radius, c, from the flame. The area of the sphere is $4\pi c^2$. The ratio of the rate of energy received to the surface area completes the deduction of Equation 3.6. The formula only applies to a target looking directly at the "center" of the flame. This simple result has been shown to have reasonable accuracy (±50%) as long as $c > 2l$.

TABLE 3.3
Typical Radiative Energy Fractions, X_r

Fuel ($l \geq 0.5$ m)	X_r
Methanol, methane	0.15–0.20
Butane, benzene, wood cribs	0.20–0.40
Hexane, gasoline, polystyrene	0.40–0.60

Source: Various.

TABLE 3.4

Specific Radiation Fraction of Combustion Energy for Hydrocarbon Pool Fires Showing Dependence on Diameter

Hydrocarbon	Pool Size (m)	Fraction
Methanol	1.2	0.17
LNG on land	0.18	0.164
	0.4–3.05	0.15–0.34[a]
	1.8–6.1	0.20–0.25[a]
	20.0	0.36
LNG on water	8.5–15.0	0.12–31.0[a]
LPG on land	20.0	0.7
Butane	0.3–0.76	0.20–0.27[a]
Gasoline	1.22–3.05	0.40–0.13[a]
	1.0–10.0	0.60–0.100[a]
Benzene	1.22	0.37
Hexane	—	0.40
Ethylene	—	0.38

Source: Mudan, K.S. and Croce, P.A., Fire hazard calculations for large open hydrocarbon fires, Chap. 3–11, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

[a] In these cases, the smaller-diameter fires were associated with higher radiative fractions.

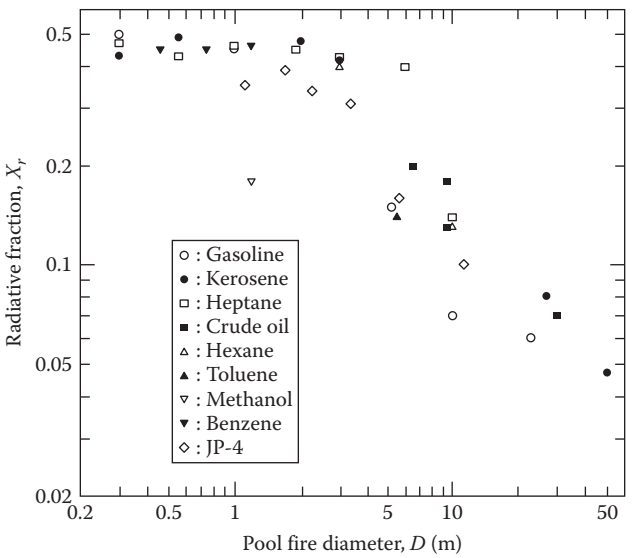

FIGURE 3.10
Radiative fraction dependence on pool diameter. (From Koseki, H., *Fire Technol.*, 25(3), 241, 1989.)

FIGURE 3.11
Illustration of soot blocking the core radiation from a large fire.

Example 3.4

For the previous calculation in Example 3.3 for wood, we can make an alternative estimate using Equation 3.6. While that example's geometry is not cylindrical, we will stretch the application to use Equation 3.6.

Select $X_r = 0.36$ (based on Figure 3.13) for a wood flame. (Figure 3.13 shows that the slope of the wood crib data is about 14/400. From Equation 3.6 this would give $X_r = 4\pi(0.9\text{ m})^2 \times 14/400 = 0.356$.) Based on an equation for flame height in Chapter 7 the 1 m tall wood flame corresponds to a firepower of about 110 kW. Therefore, from Equation 3.6,

$$\dot{q}'' = \frac{(0.36)(110\text{ kW})}{4\pi(3\text{ m})^2} = 0.35\ \frac{\text{kW}}{\text{m}^2}$$

This is very similar to the result of 0.42 kW/m^2 previously estimated for the rectangular wood fuel flame 1 m tall, 0.5 m wide and thick. The difference is due to the approximate nature of both formulas and the accuracy of the data we are using to represent the wood flame. But the differences are within the accuracy we can expect from such a calculation.

In general, fire calculations such as these could have accuracy as poor as ±50%, but usually more like ±30%. Their value lies not in perfect accuracy but in the plausibility of the fire scenario they support. For example, both of these results give heat fluxes more than that of sunlight. We would expect them to be potentially harmful. The formulas can guide us in establishing the plausibility of a hypothesis that we pose for a fire scenario. Is there a hazard or not?

3.4 Heat Flux as an Indication of Damage

Heat flux causes objects to get hot and possibly damaged or ignited. As a benchmark, the radiant heat flux from the Sun at the Earth's surface is nearly 1 kW/m^2, at most. Thresholds (minimum values) of heat flux to cause damage under fire conditions are listed as follows:

Pain to bare skin: ~2 kW/m^2
Burn to bare skin: ~4 kW/m^2
Ignition of objects: ~10–20 kW/m^2

These threshold values will cause the results indicated only after a "long" exposure of many seconds or minutes. The time to cause damage to bare skin (Figure 3.12) is illustrated from the work of Stoll and Greene.[4] In the figure, the times to achieve pain and a blister skin burn for heat fluxes higher than the threshold values are graphically shown. The threshold values appear to be approached after about 30 seconds. These threshold values give general guidelines for assessing the potential damage from the fire exposure heat flux. Therefore, it is very important to be able to estimate fire heat fluxes.

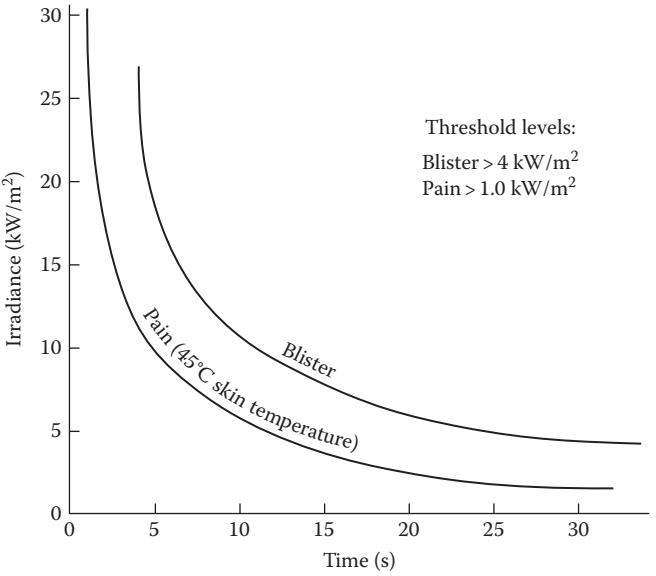

FIGURE 3.12
Incident radiant heat flux effect on bare skin. (From Stoll, A.M. and Greene, L.C., *J. Appl. Physiol.*, 14, 373, 1959.)

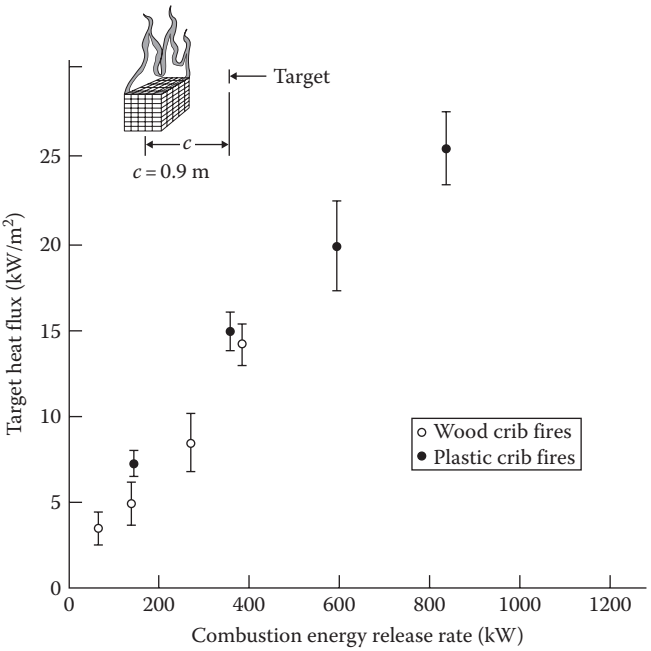

FIGURE 3.13
Radiant heat flux to a target facing 0.9 m from the center of wood and plastic crib fires. (From Quintiere, J.G. and McCaffrey, B.J., The burning of wood and plastic cribs in an enclosure, Vol. I, NBSIR 80-2054, National Bureau of Standards, Gaithersburg, MD, September 1980, p. 118.)

Unfortunately, as flame radiation is most responsible, it is the least predictable. However, experimental results can give us some empirical means to make fire estimates.

Figure 3.13 shows measurements of radiant heat flux received by a target approximately 1 m from wood or plastic cribs. The results are consistent with Equation 3.6 and yield a value of X_r between 0.30 and 0.40 for both the fuels. As cribs represent structural furniture, these radiative fractions might be used accordingly for furniture as a first approximation.

3.5 Heat Flux Due to Smoke in Room Fires

Incident radiative heat fluxes to the floor in a door-vented room fire are shown in Figure 3.14. These data come from the same tests of the wood and plastic cribs of Figure 3.13. The heat fluxes are plotted as a function of the

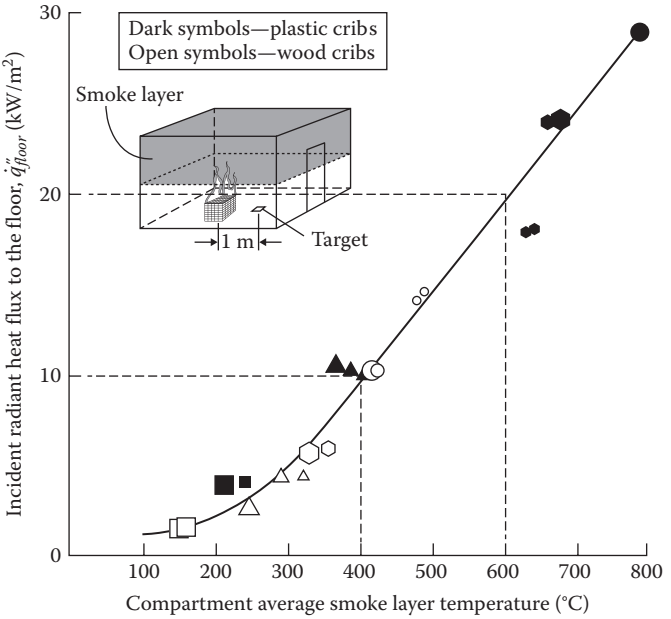

FIGURE 3.14
Incident radiative heat flux to the floor in a compartment due to hot smoke. (From Quintiere, J.G. and McCaffrey, B.J., The burning of wood and plastic cribs in an enclosure, Vol. I, NBSIR 80-2054, National Bureau of Standards, Gaithersburg, MD, September 1980, p. 118.)

upper layer smoke temperatures. Despite the variation in the type of fuel (wood and plastic) and the variation of ventilation of air through different doorway sizes, the results are almost solely dependent on the average temperature of the smoke layer. This dependence also applies to measurements of total (convective plus radiative) heat flux to a ceiling target as shown in Figure 3.15. The reason for the sole dependence of these results on the smoke layer temperature can be explained by the radiative view factor of the smoke layer to the floor or ceiling. As might be inferred by examining the field of view of both the ceiling and floor targets, the smoke layer dominates the field of view compared to any radiative contribution from the crib fire. An observer on the floor looking up sees the bottom of the smoke layer in about 50% of their forward field of view, as this layer is at about half the room height. This is a configuration (view) fraction of 0.5. The same observer, still looking up, only has a very small view angle to the flaming crib. Of course, just next to the crib, it would be highest. But even that close, it would be less than 0.5. This suggests that the smoke is the principal source of the heat flux to the floor. In contrast, the ceiling target has a view factor of 1, as it sees the entire smoke layer.

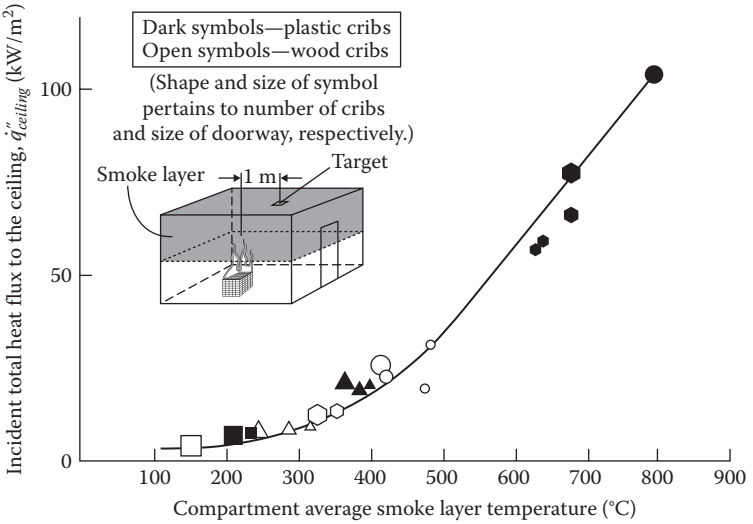

FIGURE 3.15
Incident total heat flux to the ceiling in a compartment due to hot smoke. (From Quintiere, J.G. and McCaffrey, B.J., The burning of wood and plastic cribs in an enclosure, Vol. I, NBSIR 80-2054, National Bureau of Standards, Gaithersburg, MD, September 1980, p. 118.)

Example 3.5: Confirm This Result for the Floor Heat Flux

Take a temperature of 600°C. As the smoke layer for a normal size room would be about 1 m thick, or more, we will assume it to have an emissivity of 1. Then from Equation 3.5, $\dot{q}'' = \varepsilon\sigma T_2^4 F_{12}$

$$\dot{q}'' = (1)(5.67\times10^{-11}\text{kW/m}^2\text{-K}^4)(600+273\text{ K})^4(0.5) = 16.4\text{ kW/m}^2$$

This compares to about 20 kW/m^2 as measured in Figure 3.14. Additional radiation from the crib fire likely contributes to the difference.

Consider the same smoke layer temperature for estimating the ceiling heat flux. Here, the configuration factor is 1, as an observer on the ceiling looking down would only see the top of the smoke in their field of view. From the calculation given earlier, this readily gives twice the value to the floor or 32.8 kW/m^2. But this compares to about 60 kW/m^2 from Figure 3.14. The difference here is the convection heat transfer that must be added in. These heat flux measurement sensors are cold at about 25°C. From Table 3.2, we might estimate the convective heat transfer coefficient for a plume hitting the ceiling as about 25 W/m^2-K. The convective contribution is then estimated from Equation 3.2, $\dot{q}'' = h(T_2 - T_1)$:

$$\dot{q}'' = \left(25\frac{\text{W}}{\text{m}^2\text{-K}}\times\frac{10^{-3}\text{ kW}}{\text{W}}\right)(600-25)\text{ K} = 14.4\text{ kW/m}^2$$

This gives a total of 47.2 kW/m^2, about 20% too low. But again, we have neglected any radiative contribution from the crib fire. This is within the range of accuracy we can expect. Thus, we have nearly explained the experimental results by theoretical calculations.

The threshold of piloted ignition (thin objects at 10 kW/m^2 and thick objects at 20 kW/m^2) suggests that objects begin to have a high propensity to ignite when the smoke layer temperature attains 400°C–600°C. This is why *flashover* is often associated with smoke layer temperatures at about 500°C–600°C. It is a general operational rule for static fires, but the onset of flashover has a lower critical smoke layer temperature for spreading fires. The sudden increase in spread will occur at lower smoke layer temperatures. We will have more to say about this in Chapter 9.

Figures 3.14 and 3.15 are representative of developing room fires in which there is a distinct smoke layer and distinct central fire. Once more objects get involved, flames and hot smoke will try to fill the room according to the fuel and air supply available. The flames and smoke layer can reach 1200°C or more. As the flames will be thick (>1 m), their emissivity would be near 1. In this case, the radiative heat flux could achieve 250 kW/m^2 in the room. It is not uncommon to achieve heat flux levels of 100–250 kW/m^2 in fully developed room fires.

Figure 3.16 is presented for illustration to show how radiation and convection heat fluxes can contribute to fire conditions when heating a cold object. Turbulent convective heat transfer coefficients in room fires can typically range from 5 to 50 W/m^2-K. The radiation is characterized by its

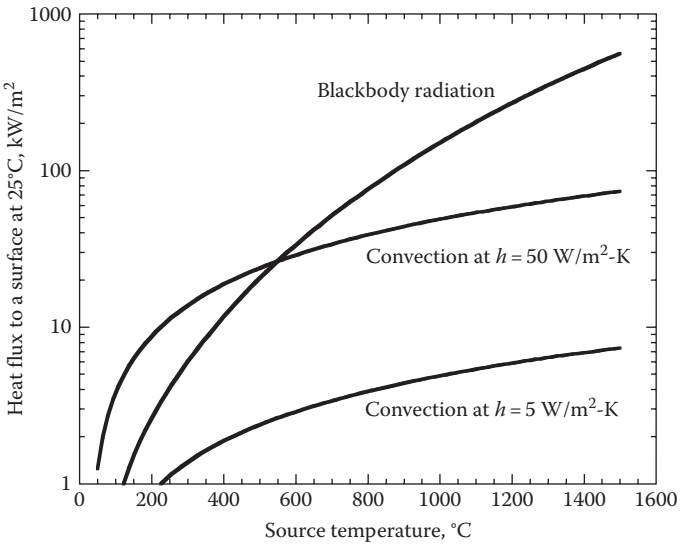

FIGURE 3.16
Overview of heat fluxes from a fire source to a cold object.

maximum potential for a blackbody. This graph puts in perspective the role of convection and radiation in fire conditions. Even at relatively low source temperatures, radiation is significant compared to natural convection (h = 5 W/m^2-K). After about 500°C, radiation truly becomes the dominant factor in heat transfer in fire.

3.6 Heat Flux from Flames

Measurements of the incident heat flux from flames to a surface can be useful in giving us a way to assess their fire hazard. The heat flux will consist of the total of the convective and radiative components. Thin laminar flame will have a higher temperature than turbulent flames (about 2000°C over 1000°C, respectively). Convection will dominate these laminar flames. Large thick flames will be turbulent, and radiation will dominate them. Lattimer[7] has assembled an assortment of turbulent flames and their heat flux behavior to surfaces. Only their peak values within the flame region will be listed here. They are listed in Table 3.5. As they can range from 20 to 200 kW/m^2, it is imperative to understand their associated fire scenarios. Commercial heat flux sensors have typically been used to obtain these measurements.

It is noteworthy to recognize that small laminar flames, such as candle and lighter flames, can achieve heat fluxes of 50–100 kW/m^2 to a surface at their tip. From the basic information given in this chapter, it is possible to explain these data, at least qualitatively.

TABLE 3.5

Turbulent Flame Peak Heat Fluxes to a Surface within the Flame

Description	Heat Flux (kW/m^2)	Comments
Corridor ceiling burning	~20	Buoyancy suppresses turbulence, thin flame
Ceiling burning, radial flame	20–30	Buoyancy suppresses turbulence, thin flame
Wall burning flame	25–40	Increases with flame height
Floor flame impinging on ceiling	80–90	High velocity, thick flame at center
Square floor fire against a wall	50–100	Increases with fire size (e.g., 50–500 kW)
Window flames from fully developed room fires (0.5 m above)	20–200	Increases with room fire size (e.g., 5–10 MW) and size of window
Objects immersed in large pool fires (10–160 m^2)	100–200	High temperature, thick flames

Source: Lattimer, B.J., Heat fluxes from fires to surfaces, Sect. 2, Chap. 14, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 4th edn., National Fire Protection Association, Quincy, MA, 2008.

3.7 Summary

Heat is energy transfer due to a temperature difference. Heat transfer is a significant process in fire. It accounts for the vaporization of the fuel, growth of the fire, and its damage. Heat flux is the rate of heat (energy) transfer per unit area normal to its direction. We sense heat flux as we might be exposed to a fire.

There are three categories of heat transfer: (1) conduction, a molecular phenomenon; (2) convection, conduction in a moving fluid; and (3) radiation, an electromagnetic phenomenon. The laws of Fourier and Planck provide the bases for conduction and radiative heat transfer calculations, respectively.

Conduction heat flux is directly proportional to the difference of temperature, while radiation depends on the fourth power of the absolute temperature. Absolute zero is the lowest temperature possible.

Heat flux is a key parameter in assessing the potential damage by a fire. Threshold heat flux levels are approximately 2 kW/m^2 for pain to bare skin, 4 kW/m^2 for a burn to bare skin, and 10–20 kW/m^2 for the ignitions of objects. Flames can cause heat fluxes of 20–200 kW/m^2, depending on their size and shape.

The smoke layer temperature in compartment fires of 500°C–600°C is frequently taken as a benchmark for the initiation of flashover.

Review Questions

1. What is the difference between the absolute temperature scale and the Celsius scale?
2. What distinguishes heat from other forms of energy?
3. How long will it take heat to penetrate a 3 in. thick concrete wall?
4. Estimate the convective heat flux from a match flame to the surface of its wood. The flame is roughly 1900°C and the wood pyrolyzes at 350°C. The convective heat transfer coefficient can be taken as 50 W/m^2-K as an estimate.
5. Estimate the convective heat flux from a gasoline turbulent pool fire to the evaporating gasoline surface. Gasoline evaporates at roughly 33°C during burning conditions. Its turbulent flame temperature is 800°C on average. Take the convective heat transfer coefficient as 20 W/m^2-K (see Table 3.2).
6. For the fire in Problem 5, estimate the radiative heat flux to the liquid surface. Assume a flame emissivity of 0.5. For a target on the surface how much of the flame does it see?

7. Compute the radiant heat flux 20 m from an 8 MW gasoline pool fire. Assume the fire is 3 m in diameter. If the fire diameter doubles, the firepower will increase by a factor of 4. Use Figure 3.10 to make these estimates.

True or False

1. Convective heat transfer is a type of conduction.
2. Conduction depends on molecules, radiation on electromagnetic energy, and convection on ether rays.
3. The emissivity of a surface should be less than one, but for a large flame it can easily be one.
4. Thermal conductivity and thermal diffusivity are properties of a solid controlling its heat transfer.
5. A threshold for a skin burn could be 4 kW/m^2, while at 10 kW/m^2 we could have ignition of clothing.
6. Heat is not a form of energy.
7. A guide for the onset of flashover in a room fire is when the smoke reaches 500°C–600°C.
8. Laminar small flames always have lower heat fluxes than turbulent flames.
9. Zero absolute temperature indicates that there is no more energy in the material.
10. Mass can change into energy in a chemical reaction.

Activities

1. Find out how much time is needed to melt an ice cube. Look up the energy needed to melt ice (heat of fusion, J/g). Estimate the convective heat transfer coefficient for a cube sitting in still air. Note that the ice temperature is always 0°C and record the room temperature. Compare your computed time to the actual time. Explain the differences.
2. Make a heat flux meter. Connect a thermocouple to a thin (1/8 in.) metal disk about 1 inch in diameter. Insulate the back of the disk very well. Roughen the disk and deposit soot on it from a candle flame or paint it flat black. This will tend to make its emissivity 1. If the disk is thin enough, when the meter is exposed to a higher heat flux, its surface will get hot. If no heat is lost through the insulation, all of heat received will

radiate away. The heat flux radiated away will be exactly equal to that received. The emitted heat flux is computed by using Equation 3.3 and the measured temperature. Using the heat flux meter in cold air will cause a convective heat loss as well, and this would need to be considered as a source of error. Or this convective heat flux can be added to the emitted radiant heat flux. The total is the heat flux received.

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7. B. J. Lattimer, Heat fluxes from fires to surfaces, Sect. 2, Chap. 14, in *SFPE Handbook of Fire Protection Engineering*, 4th edn., edited by P. J. DiNenno (Quincy, MA: National Fire Protection Association, 2008).

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Ignition

Learning Objectives

Upon completion of this chapter, you should be able to

- Explain the difference between piloted ignition and autoignition
- Define evaporation
- Explain flashpoint and fire point
- Describe the ignition processes in liquids and solids
- Describe the concept of ignition temperature for solids
- Use formulas to predict the ignition time of solids

4.1 Introduction

In Chapters 4 through 6, we discuss the essence of fire growth, which is composed of ignition, flame spread, and burning rate. These are distinct fire processes that may have some features in common but must be put together to establish fire growth. We will clarify their common characteristics and their differences. This chapter discusses ignition, the start of fire growth. Ignition is very important, as without it there would be no fire. It is a step that is easily recognized for flaming ignition and is subtle to discern for ignition to smoldering. Ignition can occur in different ways, but always heat should be added. Sometimes, this heat is localized in the form of a small flame or distributed over a region of the fuel.

4.2 Piloted Ignition and Autoignition

Ignition was discussed in Chapter 2 for gaseous fuels. It has two forms: piloted ignition and autoignition. The former is the process of initiation and flame propagation in premixed fuel systems. The minimum condition for piloted ignition occurs at the lower flammable limit (LFL)—that concentration of fuel that allows propagation with a small sufficient heat source (pilot). This pilot can be an electric arc that possesses a very high temperature or a small flame. We saw this process occurs in Chapter 2 when the candle flame was blown out and the white vapor trail was then ignited. (What happens when we ignite the candle by applying a flame to the wick?)

The second form of ignition is autoignition that occurs without any pilot. The fuel must still be within a specific concentration range, typically between the lower and upper flammability limits. Also, chemical kinetic processes must generate energy production to exceed the heat loss of the fuel gas–air mixture. The piloted ignition and autoignition of liquid and solid fuels occur in an identical fashion for their evaporated or decomposed gas–air mixtures. This is illustrated in Figure 4.1. The gaseous fuel evolves by heat transfer and mixes with air. A pilot can cause the ignition, or the hot surface of the solid in Figure 4.1 might cause ignition. The latter would be autoignition and would occur in the case of radiant heating of wood. In both cases, a sufficient fuel gas concentration must be generated.

4.3 Evaporation in Liquids

Liquids generate fuel as a vapor or gas. This process continuously occurs at the surface. The liquid in Figure 4.1 evaporates at a sufficient rate to form a concentration near the pilot source at the LFL to allow ignition. The rate

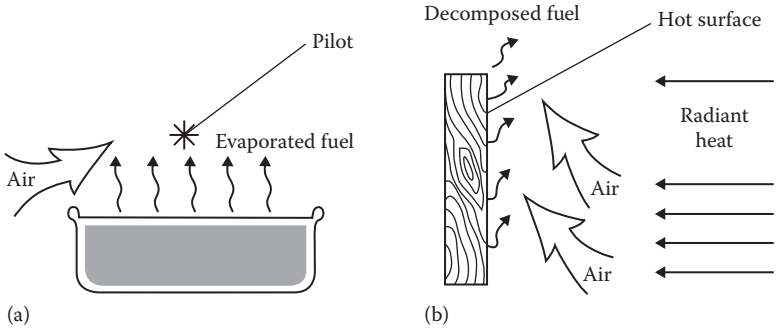

FIGURE 4.1
Ignition processes in (a) liquids and (b) solids.

of evaporation is controlled by the liquid temperature. Let us examine the process of evaporation for water, as an example. Water will evaporate relatively slowly under normal room temperature. At the liquid temperature, or energy level, only a relatively small amount of water molecules can break out of the surface and enter the adjacent air. The escaping vapor creates a pressure that contributes to the total pressure of the atmosphere. Atmospheric pressure is normally 14.7 psi or about 10^5 Pa (1 bar). This "partial" pressure of the water vapor is contributing to the total 1 bar pressure is called vapor pressure.

The vapor pressure can be more properly defined as the pressure where a liquid and its vapor are in equilibrium (a state of balance) for a given temperature. For pure liquid substances, this relationship between vapor pressure and temperature is a property of the material. In general, the vapor pressure is a strong function of temperature and increases sharply as the temperature rises. For example, water at 25°C has a vapor pressure of 0.032 bar (or 0.032 × 14.7 psi = 0.47 psi), which is relatively very small. But as the liquid temperature is increased, more molecules escape (evaporation) until 100°C (212°F) is reached. Here, the vapor pressure of water is now about 1 bar (or precisely 1.014 bar). Now all of the escaping water vapor molecules make up the total pressure of the surrounding pure air above the liquid. This means that the vapor at the liquid surface no longer contains any air, or in other words, its concentration is 100%. At normal atmospheric pressure, this is the maximum temperature that the liquid water can achieve. In fact, the water vapor concentration (in molecular or molar terms) is equal to the vapor pressure divided by the total atmospheric pressure (1 bar). At 25°C, water has a concentration of 3.2%. This concentration is commonly referred to as volume concentration as it corresponds to the volume of water vapor in a measuring device formed by extracting it from the air–water mixture and allowing it to expand at a normal atmospheric pressure (see Figure 4.2).

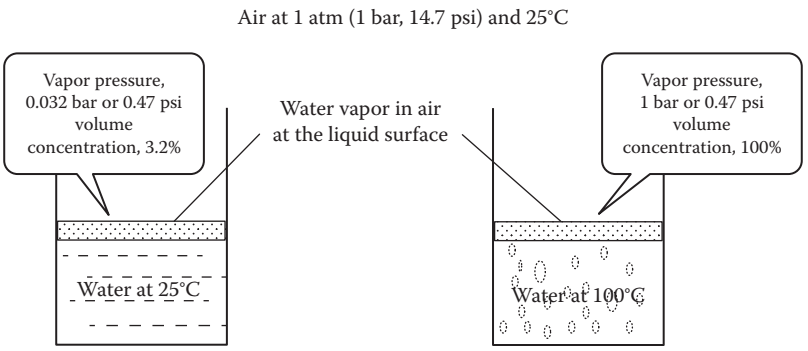
Air at 1 atm (1 bar, 14.7 psi) and 25°C
Vapor pressure, 0.032 bar or 0.47 psi volume concentration, 3.2%
Water vapor in air at the liquid surface
Vapor pressure, 1 bar or 0.47 psi volume concentration, 100%
Water at 25°C
Water at 100°C

FIGURE 4.2
Water vapor in air.

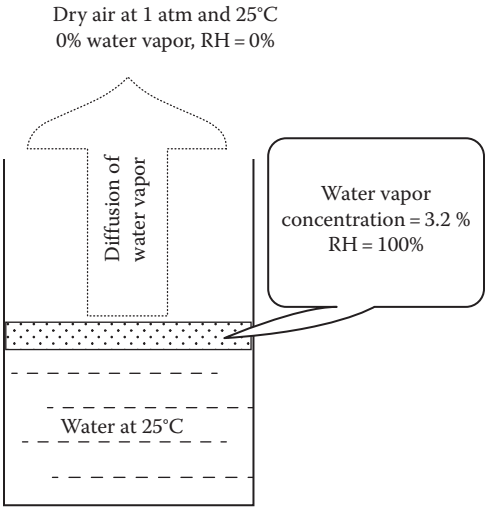

FIGURE 4.3
Relative humidity and diffusion.

For water in air, relative humidity (RH) is a measure of how much water vapor can be contained in the air. For example, at 25°C if the concentration of water vapor were 1%, its RH would have been 1/3.2 × 100% or about 31%. (In other words, 31% of the volume of water vapor that could be contained in the air is present.) Water vapor will continually leave the surface of the liquid and enter the bulk air at this RH. If the air is initially "dry" (0% RH), the liquid will continue to evaporate as long as there is a higher concentration of vapor at the surface than that of the bulk air. The transfer of water vapor from the surface to the air occurs through diffusion. (Diffusion is the motion of a species [e.g., vapor] from a high to low concentration.)

The air above the liquid can enhance this transfer process over that of pure diffusion. This effect due to airflow is called convection with respect now to mass transfer analogous to convection in heat transfer. If the air reaches 100% RH, there will now be no difference between the concentration of the water vapor at the liquid surface and in the bulk air, so evaporation will cease (see Figure 4.3). This is why laundry will not dry in air at 100% RH.

4.4 Liquid Fuels

Pure liquid fuels behave exactly as water. Mixtures of fuels will evaporate depending on their components. The more volatile components (higher vapor pressure) will evaporate first in hydrocarbon mixtures such as gasoline.

Let us stick to a pure liquid model for ease of explanation for ignition. But remember, in liquid fuel mixtures, it is the more volatile component controlling ignition.

4.4.1 Piloted Ignition

At piloted ignition, the surface concentration needs only to achieve the LFL. At this concentration, the corresponding surface temperature is called the flashpoint (T_{FP}). The pilot at the LFL initiates a propagation of flame in the atmosphere above the liquid surface. This flame is a premixed flame. It will propagate as long as the mixture is in the flammable range. Hence, the name flashpoint applies, as this process would appear as a "flash." The flash could impart more heat to the liquid surface causing its temperature to rise. This action would cause an increase in the vapor pressure with more evaporation. If the evaporation rate continues to increase, it is possible that a stable diffusion flame will form above the liquid surface. The minimum liquid temperature to allow a stable diffusion flame is called the fire point (fire point is the minimum liquid surface temperature needed by the liquid to sustain a diffusion flame).

For example, *n*-decane, a liquid at normal room temperature, has a measured flashpoint between 44°C and 52°C and a fire point of roughly 62°C–66°C. (The variations in these results are due to the way the measurement is made. The location of the pilot and the corresponding concentration of vapor will affect the results.) The maximum temperature the *n*-decane can achieve is 174°C, its boiling point (boiling point—the maximum temperature a liquid can achieve in air).

The boiling point is the temperature corresponding to when its vapor pressure equals to the exposed atmospheric pressure. Here, the fuel concentration is 100% at the surface. Once a diffusion flame is formed, the heat transfer from the flame to the surface is sufficient to achieve nearly the boiling point. This fact allows the boiling point to be the assumed liquid surface temperature in a fire.

The process of piloted ignition has led from a premixed flame to a diffusion flame. This process takes a little time. Therefore, the time required for "ignition" to occur is somewhat problematic, as it could be designated at either the flashpoint or the fire point. However, the time difference between these events is normally small.

The range of these critical temperatures for some liquid fuels is shown in Table 4.1.

Because the normal atmospheric temperature is roughly 22°C, everything above ethanol in Table 4.1 can easily ignite with a pilot under normal conditions. Extra heat should be provided to *n*-decane, kerosene, and higher flashpoint liquid fuels to bring their surface to the flashpoint.

TABLE 4.1

Critical Temperatures for Liquid Fuels in °C[a]

Liquid	Formula	Flashpoint	Fire Point	Boiling Point	AIT	Hot Surface Ignition
Propane	C_3H_8	−104	—	−42	450	—
Gasoline	~C_8H_{18}	~−45	—	~33	371	>560
Acrolein	C_3H_4O	−26	—	53	235	—
Acetone	C_2H_6O	−18	—	56	465	—
n-Heptane	C_7H_{16}	−4	−1	98	233	670
Methanol	CH_3OH	12	17	64	385	690
Ethanol	C_2H_5OH	13	—	78	363	690,717
n-Decane	$C_{10}H_{22}$	44–52	62–66	174	210	—
Kerosene	~$C_{14}H_{30}$	49	—	232	260	650
m-Creosol	C_7H_8O	86	—	203	559	—
Formaldehyde	CH_2O	93	—	97	430	—
Motor oil	—	186,216	224	300–560	351	310,740

Sources: Zabetakis, M.G., Flammability characteristics of combustible gases and vapors, Bulletin 627, Bureau of Mines, U.S. Department of the Interior, Washington, DC, 1965; Babrauskas, V., *Ignition Handbook,* Fire Science, Society of Fire Protection Engineers, Publisher, 2005; Tewarson, A., Thermophysical and fire properties of automobile plastic parts and engine compartment fluids, Vol. III, Tech Report #0003018009, FM-Global, Norwood, MA, October 2005.

[a] Results can vary due to the test used; AIT data commonly from the spherical vessel test.

4.4.2 Autoignition

The process of autoignition is a slightly different mechanism compared to piloted ignition. As indicated in Figure 4.4, autoignition occurs at a concentration generally between the upper (UFL) and the lower (LFL) flammability limits. The stoichiometric state in which all the fuel vapor and all the oxygen

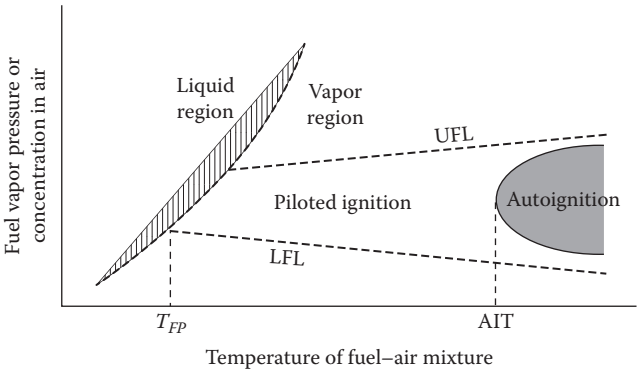

FIGURE 4.4
Conditions needed for ignition.

in air are consumed is most favorable for autoignition. Autoignition is synonymous with spontaneous combustion or "self-ignition." This ignition inherently occurs due to an imbalance, triggered at the critical temperature, between the chemical energy production and the local heat loss in the gas. The temperature at which this occurs is the autoignition temperature (AIT). Once a flame results in a small region, the process becomes much like piloted ignition, as a premixed flame is propagated through the remaining flammable mixture.

As seen from Table 4.1, the AIT is mostly higher than the boiling point. For a liquid to autoignite, some hot surface must heat the vapor–air mixture to the AIT. But this temperature is not unique and depends on many factors related to the hot surface heat transfer. The values given in Table 4.1 listed as AIT undoubtedly came from a standard test in which an open spherical vessel was placed in an oven. The vessel size and concentration–temperature distribution of the mixture makes the measurement not so precise. Bigger vessels give a lower AIT in such a test. ASTM E-659 is an example of a standard test for determining the AIT for liquid chemicals.

In another configuration of heat, such as that of a hot surface exposed to the mixture, gives much different results than the spherical vessel oven test. This scenario can occur when a liquid fuel is sprayed on a hot surface. Measurements have also been made for ignition by a hot surface. The surface temperature is typically much higher than the AIT (by the vessel test). The temperature of the surface to cause ignition depends on the nature of the surface, the way liquid contacts the surface, and the air velocity. Some values of "hot surface ignition" are given in Table 4.1, but they should be taken as rough indications, not definitive values.

Note that the AITs of the liquid fuels are much higher than their flashpoints and boiling points. Indeed, all of the liquid would be vaporized at these AITs. One exception to this difference is asphalt in which the AIT is nearly the same as its boiling point, about 480°C. An example of a fire involving asphalt for a roofing application illustrates an interesting scenario. A heated kettle was used to liquefy the asphalt. As its temperature became too high and into the boiling range, the liquid ignited when it was tapped from the kettle. As the liquid came in contact with air, the vapor–air mixture was now at the AIT. This incident was initially suspected as an arson fire.

Under actual fire conditions, both autoignition and piloted ignition apply as competent scenarios. However, the piloted ignition case is probably more predominant once a flame exists in accidental fires. The vapor trail of a liquid fuel spill may travel some distance before finding a pilot source. This is a common scenario due to spilling a liquid fuel near a water heater with a pilot flame as illustrated in Figure 4.5.

In another ignition scenario, a halogen light bulb was suspected of being the ignition source during paint spraying in a confined space. Indeed, it was determined that the AIT temperature of the paint (by a vessel test method) exceeded the light-bulb temperature. However, this scenario would be a hot surface ignition case. Spraying paint on the bulb and evaporating the paint

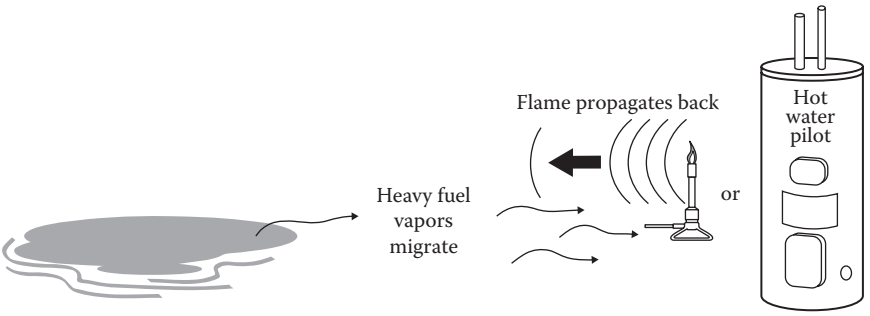

FIGURE 4.5
Evaporating liquid, remote ignition.

within its lens housing indicated no ignition. The hot surface ignition temperature was much higher than that reported by the vessel test.

Another surface not sufficient to trigger ignition is the lit cigarette for gasoline. This scenario depicting in countless movies has been shown to not occur in repeated tests. Indeed, several years ago in a student project this was shown dramatically by evaporating gasoline at the bottom of a vertical cylindrical tube open at the top. Holes in the vapor region of the tube allow a competent pilot flame to be inserted to indicate the region of flammability. When a lit cigarette was placed in the same region, even with a device to draw on the cigarette, no ignition occurred. It has also been reported that numerous tests of a lit cigarette tossed into a pool of gasoline showed no ignition.

4.5 Solid Fuels

Flashpoints for liquids can be measured with reasonably good precision and can also be computed from theory. But the ignition temperatures of solids are not precisely determined. They depend on the decomposed fuel concentration, its components, and the way the solid is heated. The formation of porous char may contribute to its variation. As a result, solid ignition temperatures published in the literature can only be taken as rough indications. Often, these data depend on the experimental conditions or the analysis used to derive them. Moreover, it is very difficult to directly measure the surface temperature up to the point of ignition. Despite this limitation on establishing a definitive ignition temperature for a solid fuel, experimental results will give us some reasonable approximate values. These and other results can be used to make quantitative estimates on the prospect of ignition and the time it can take. We will examine some

predictive models for solid fuel ignition based on the use of effective or approximate ignition temperatures and other properties.

Let us first examine the processes involved in the ignition of a solid more closely. Solid fuels tend to be mostly polymers, either synthetic or natural. Wood is a natural polymer. A polymer is a compound made up of large molecules consisting of linked chains of a repeated chemical structure. The chemical structure is called a monomer—a repeated chemical structure in a polymer.

For example, the chemical structure alone as C_2H_4 is ethylene, a gas at normal atmospheric conditions. But the structure linked as the monomer—C_2H_4—is now polyethylene, a solid under normal conditions. In order to get polyethylene to ignite, it must first be vaporized. While a pure substance, such as ethylene, remains the same chemical while it is a solid, liquid, or gas, this is not true for polyethylene. When polyethylene is heated, it will start losing its structure melting at about 120°C–145°C and will have a reported flashpoint of greater than 220°C. In reality, the melt may not be a true liquid to a polymer scientist but just a "softened" solid. Above 220°C where ignition is possible, vapor must be generated. The vapor is due to thermal decomposition (or pyrolysis—the production of vapor by heat from a decomposing solid). The polyethylene is thermally broken into other chemical compounds that make up the vapor produced.

For some polymers, this vapor could ideally be the monomer, but mostly it is not. The vapor is likely a complex mixture of hydrocarbons. The vapor produced by the decomposition of the solid is not the same fuel chemically as in pure liquid evaporation. Whatever it is, it must still achieve the LFL of that mixture to be ignited in piloted ignition or must be in at a flammable concentration and at the AIT for autoignition. The flame processes are the same for the liquid and solid fuels; only, the vaporization process is different. The liquid retains its chemical structure, whereas the solid does not as it decomposes to a vapor. The vapor pyrolysis products for wood will consist of many compounds. Some will condense in the atmosphere as fine droplets (tars), displayed as white "smoke." Wood, like some synthetic polymers, will not totally decompose to a vapor but will leave behind a carbonaceous porous char.

4.5.1 Ignition of Wood as an Example

Wood can exemplify the full range of factors affecting the ignition of solids. First, wood can contain absorbed water. When the wood is heated to 100°C, water vapor will diffuse both into and out of the wood. The released water vapor will increase the LFL of the air–fuel vapor mixture and retard ignition. In addition, the water vapor can be trapped in pockets of virgin wood and the char. This trapped vapor can lead to centers of locally high pressure that are usually relieved by cracks. The process is much the same as the more

explosive moisture cracking in heated concrete known as spalling (spalling—explosive breaking of concrete due to the vaporization of trapped water or other liquids).

Second, the formation of char on the surface can play the role of an insulator to heat conduction into the virgin wood. The char is also a source of chemical energy as the char oxidizes from air diffusing to the surface. While this oxidation will release insignificant energy at low temperatures, it could eventually lead to full-blown ignition to smoldering. This solid-phase ignition might be termed *glowing ignition* as the surface will likely turn red (glowing ignition—start of smoldering at a high enough temperature to emit red light.)

In theory, the onset of smoldering ignition is an imbalance between the chemical energy released and the heat losses that result in a sudden jump in temperature at the surface. The energy released by smoldering can play a role in enhancing the piloted ignition and autoignition of wood.

Third, the decomposition of wood is not like polyethylene, a melting solid. Wood thermally decomposes to char and vapor. The vapor will be composed of a complex array of molecules from low volatility to heavy tars. The mixture of vapors depends on the rate the wood is heated, so the LFL of the mixture will not be a precise constant for wood. The LFL is known to theoretically depend on the heat of combustion. The heat of combustion for wood volatiles can range from about 10 to 15 kJ/g, so a ±25% variation can be expected in the LFL for the wood volatiles. In general, the LFL is low—typically about 1%–3%. So, a small quantity of fuel vapor is only required for piloted ignition in all cases. In a pure liquid, the transition to vapor is dependent on a vapor pressure–temperature property relationship. This is a precise property. For a solid, vaporization depends on the chemistry of pyrolysis. Yet, both vaporization processes are a strong function of temperature. As the wood nears a critical temperature, it will produce the needed vapor concentration for ignition. This temperature at the surface to achieve the minimum concentration for piloted ignition or autoignition, we term as the ignition temperature (ignition temperature—effective surface temperature to cause ignition of the emitted vapors).

4.5.2 Ignition Temperature and Critical Heat Flux

Some experiments on the wood heated by a radiant source in air will serve to illustrate the conditions critical to ignition. These experiments come from the work of Spearpoint[4] and Boonmee.[5] Critical surface temperature to cause ignition of redwood heated by radiation was measured for the different modes of ignition: (1) glowing ignition, (2) piloted ignition, and (3) autoignition. The onset of glowing ignition was designated when the wood surface temperature exceeded that of an inert insulator exposed to the same radiant heat flux. This rise showed that the wood surface was now producing significant energy due to oxidation. These results are indicative of the variation

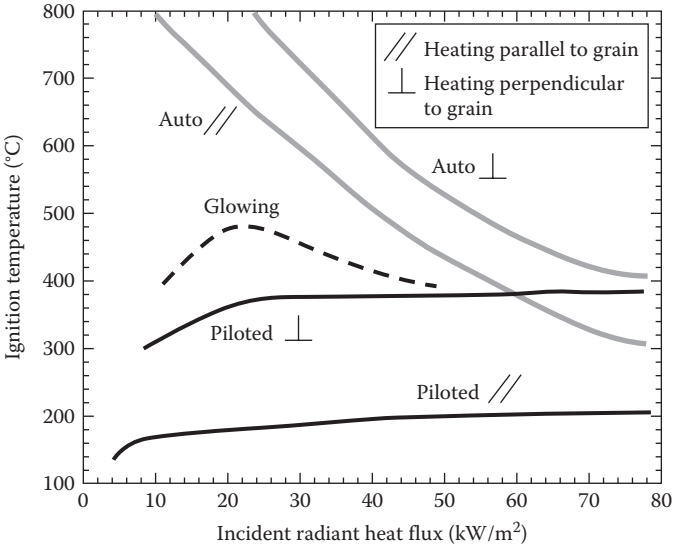

FIGURE 4.6
Surface temperatures at ignition for redwood considering flaming (auto, pilot) and smoldering (glowing), when heated perpendicular and parallel to the wood grain. (From Spearpoint, M.J. and Quintiere, J.G., *Fire Safety J.*, 36, 391, 2001; Boonmee, N. and Quintiere, J.G., *Proc. Combust. Inst.*, 29, 289, 2002.)

in ignition temperature for a charring material. Figure 4.6 displays the trend lines of the temperature data. It is seen that for piloted ignition and autoignition the ignition depends on whether the wood was heated parallel or perpendicular to its grain. The ignition temperatures are lower for parallel heating as it is easier for the volatiles to escape along the wood grain paths. For both heating directions, the AIT is higher than that of piloted ignition. The glowing ignition temperatures could only be noticed below 40 kW/m^2, as the time to ignite by flaming was too fast above 40 kW/m^2 to discriminate glowing before flaming. The glowing temperature is always between piloted and AIT. Below 40 kW/m^2, the mechanism for autoignition is distinctly a transition from smoldering to flaming. Thus, at low heat flux, smoldering will persist for a long time before flaming ensues. As the char layer builds up and further insulates, the surface temperature can rise to as much as 900°C before flaming occurs. This hot surface is now the heat source for ignition to flaming.

The times for ignition of this redwood are shown in Figure 4.7. Above 40 kW/m^2, it is difficult to distinguish a difference between autoignition and piloted ignition, as the ignition times are of the order of about 10 seconds or less. Below 40 kW/m^2, glowing ignition can slightly precede piloted ignition, but the difference is not significant. The coincidence of these events must follow, as the onset of char needed for glowing ignition also denotes the time of decomposition to fuel vapor. While glowing ignition might occur

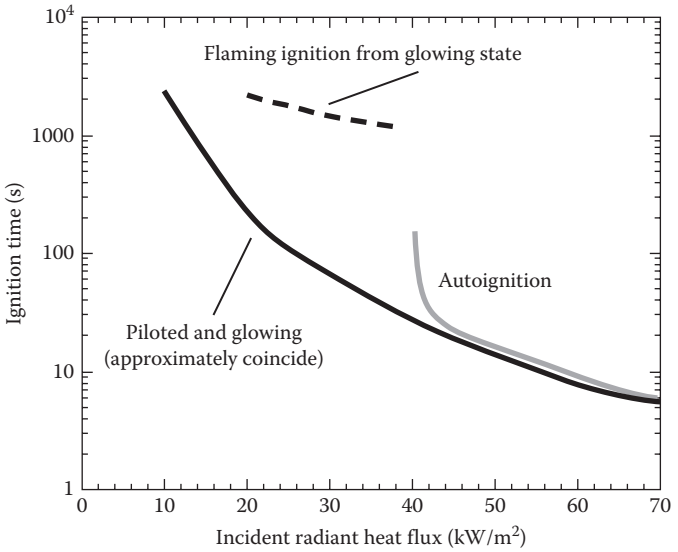

FIGURE 4.7
Ignition times for redwood as a function of incident radiant heat flux. (From Spearpoint, M.J. and Quintiere, J.G., *Fire Safety J.*, 36, 391, 2001; Boonmee, N. and Quintiere, J.G., *Proc. Combust. Inst.*, 29, 289, 2002.)

in 100 seconds at about 25 kW/m^2, the subsequent transition to flaming or "autoignition" can take over ½ hour. Below 20 kW/m^2, it appears that this transition will not occur. But an increase in air velocity or simply waiting longer could discount this limit. The critical limits for piloted and glowing ignition appear to be about 10 kW/m^2 for ignition times approaching about 1 hour. The critical heat flux (CHF) for direct flaming in autoignition of the redwood, without the transition from smoldering, is about 40 kW/m^2. In general, under radiant or direct flaming ignition, there will be a CHF that just allows the surface temperature to reach its ignition temperature. This will depend on the nature of heating and the convective state of the environment.

4.6 Time for Flaming Ignition

The time for flaming ignition of liquids and solids involves three steps. The first is predominately the longest. This is the time to heat the liquid or solid to achieve sufficient vaporization. If the liquid is motionless, conduction heat transfer solely controls the heating within the liquid, as well as a solid. The agent for heating could be radiant, convective, or conductive

heating at the surface and could involve direct flame impingement. The incident heat flux of this agent is significant as it must be sufficient to achieve vaporization. Such CHFs are indicated for redwood in Figure 4.7.

The second and third steps are usually small. The second step is the time for the fuel vapor and air to mix into a flammable mixture. This mixing process is controlled by diffusion or convection and is roughly a few seconds after vaporization occurs at the surface. For piloted ignition, it involves the time to reach the pilot.

The third step is the time it takes for the chemical reaction to release enough energy to be perceived as a flame. For a piloted condition this is generally less than a second, as the pilot flame or electric arc provides a very high local temperature. For autoignition, this reaction time can be much longer. The AIT (spherical vessel test) of kerosene is listed at 221°C. This is the minimum temperature to cause ignition of a flammable mixture. At higher temperatures, autoignition will occur more quickly. Figure 4.8 suggests that at 221°C, ignition of kerosene can take more than 100 seconds. In general, the autoignition of gases can take much longer than for corresponding piloted ignition.

In considering these steps, it is generally found that the longest and most significant step, at least in piloted ignition, is the first one. This is the time to heat the surface to achieve sufficient vaporization capable of ignition. Flammable concentrations are small and occur quickly. Therefore, pure conduction heating within the solid or liquid controls most of the process.

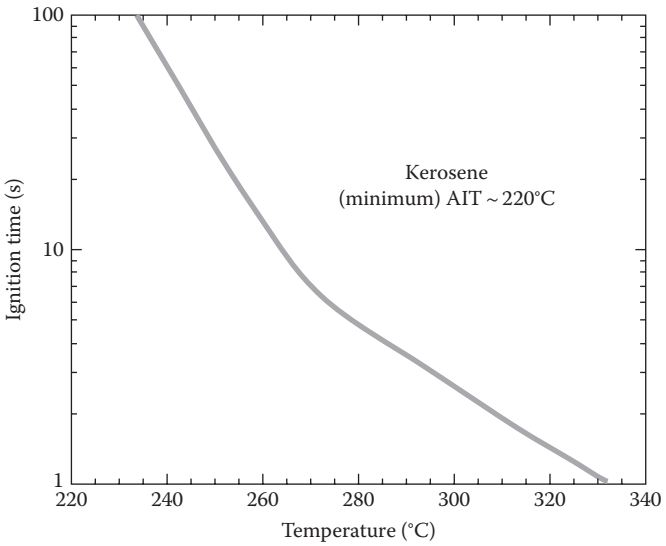

FIGURE 4.8
Autoignition time for kerosene vapor to ignite in air. (From Babrauskas, V., *Ignition Handbook*, Fire Science, Society of Fire Protection Engineers, Issaquah, WA, 2005.)

Predicting the time to ignite becomes an exercise in heat conduction to realize the ignition temperature.

4.7 Predicting the Ignition Time for Solid Fuels

From experiments, we can expect piloted ignition temperatures for solids to range from approximately 250°C to 450°C, with AIT exceeding 500°C. Fire applications comprise a wide range of materials and commercial products; it is not possible to have exact thermal data available for each. However, special fire test data can allow us to obtain effective properties for items ranging from curtains to countertops. These effective properties can enable us to estimate ignition times under a range of fire conditions.

As we have seen, the key parameter in determining the ignition of solids (and liquids) is the surface temperature. If and when that surface attains the ignition temperature is key to the ignition time. Not only will this depend on the way the heating occurs and the properties of the material but also on whether the material is "thin" or "thick." Thin is not just a physical dimension but applies under slow heating that produces a temperature is uniform throughout the thickness. Except for very slow heating conditions, "thin" is a physical thickness of 1–2 mm, or less than 1/16 in. So, single sheets of paper, drapes, and garments could be representative of thin objects in a fire environment. Anything above this dimension is considered to be thick. Even wallpaper on plasterboard is considered thick, as the paper and plaster must be considered a composite assembly. In general, it is not just the thickness that controls whether a material is thermally thin, but it is also the heat flux. At low heat flux, the physical thickness, for the thermally thin condition, increases. (Thermally thin refers to a material that has a nearly uniform temperature during heating.)

A criterion for thermally thin is

$$\text{Physical thickness} \leq \frac{2k(T_{ig} - T_{\infty})}{\dot{q}_i''}$$

For example, if the incident heat flux is 10 kW/m^2, k is 0.15 W/m^{2}K, and $(T_{ig} - T_{\infty})$ is about 300°C, then the physical thickness need only be less than 9 mm or about 3/8th in. For 50 kW/m^2, this becomes 1.8 mm. The lower heat flux produces a large thermally thin criterion.

Our discussion here can also apply to liquids provided the liquid is motionless, as would be the case if uniformly heated from the top. But heating from below or localized heating will cause motion. Motion could make the liquid act as if it were thermally thin.

4.7.1 Ignition of Thin Objects

Two cases of thin heating are shown in Figure 4.9. An object of thickness l heated from one side and perfectly insulated on the other (a) or the same object of thickness $2l$ symmetrically heated and cooled (b). The incident heat flux is given by $\dot{q}_I''$, and it may be considered radiative or from a flame. There is a heat loss flux $\dot{q}_L''$, which can be both radiative and convective. If an object is to increase in temperature, $\dot{q}_I''$ must be greater than $\dot{q}_L''$, and this difference should be great in order to achieve the ignition temperature.

This heat flux is converted into internal energy of the solid material raising its temperature. How fast that happens depends on the capacity of the solid to store energy. This energy storage capacity is measured by ρcl, the product of ρ, the density, c, the specific heat, and l, the thickness. This energy storage has the following units:

$$\rho cl \sim \frac{\text{kg}}{\text{m}^3}\frac{\text{kJ}}{\text{kg-°C}}\text{m} = \frac{\text{kJ}}{\text{m}^2\text{-°C}}$$

It tells how many kJ of energy can be stored in a square meter of this thin material to raise its temperature 1°C. A balance of energy needed to raise the temperature from T_∞ to T_{ig} must be supplied by the heat flux. The heat flux times the time gives heat added per unit area or kJ/m² in the units discussed here. The energy required equals the heat added, or

$$\rho cl(T - T_\infty) = (\dot{q}_I'' - \dot{q}_L'')t$$

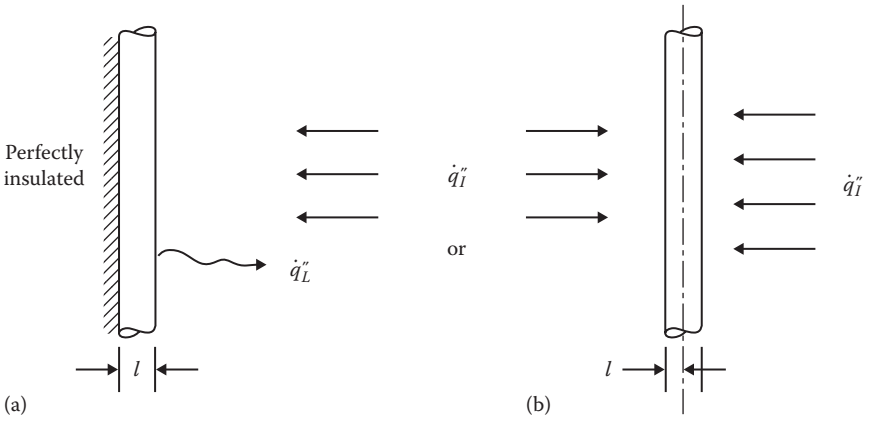

FIGURE 4.9
Heated thin objects (a) heat from one side and (b) symmetric heating.

This result is only approximate as it has ignored the fact that the temperature is increasing over time and the surface heat loss ($\dot{q}''_L$) is increasing too, as it depends on temperature. This heat loss can be by radiation and convection to the surroundings. The formula is only reasonably valid at early time. At later times, the heat losses bring the temperature to equilibrium or steady state.

As a result, the temperature of the thin solid will increase in early time (t) as

$$T = T_\infty + \frac{(\dot{q}''_I - \dot{q}''_L)t}{\rho c l} \tag{4.1}$$

where T_∞ is the initial temperature, and later in time the incident heat flux will equal the heat loss flux. The CHF needed to just achieve the ignition temperature is the heat loss flux at that temperature.

The actual temperature response over time is more completely shown in Figure 4.10 with a labeled ignition temperature (T_{ig}). When T_{ig} is reached, we have ignition (piloted or auto, depending on our selection of the value for T_{ig}). The determination of the time to ignite is shown in the figure; but under low heating conditions, T_{ig} may never be achieved. Note the CHF just causes the attainment of the T_{ig} value. For the high heating rate cases above the CHF, the ignition time can be computed using Equation 4.1. A useful approximate formula for predicting the time to ignite is

$$t_{ig} \approx \frac{\rho c l (T_{ig} - T_\infty)}{\dot{q}''_I} \tag{4.2}$$

when the incident heat flux is greater than the CHF.

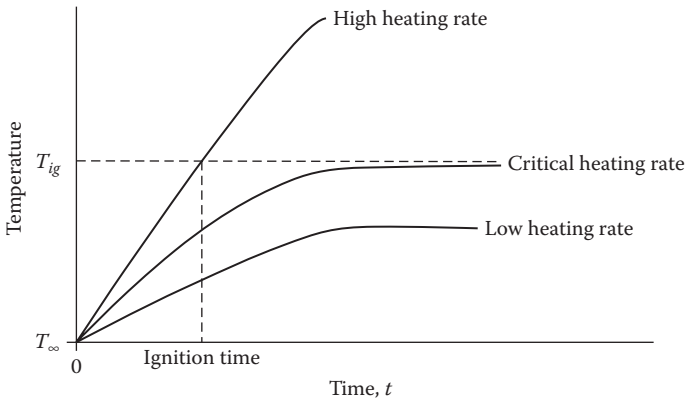

FIGURE 4.10
Temperature rise.

Example 4.1

Let us consider a typical material that might represent a drapery or a thin fabric on an insulating substrate, similar to a cushion or upholstered product. Representative properties for a cotton-like material are $\rho = 0.57$ g/cm^3, $c = 0.34$ cal/g-K, and $l = 1$ mm. For $T_{ig} = 300$°C, ignition times range from 5 to 25 seconds for a range of radiant heat fluxes between 40 and 10 kW/m^2, respectively. For $T_{ig} = 400$°C, these times only increase by about 25%. For this reason, these objects can ignite very quickly regardless of their precise ignition temperature. The heat capacity factor, ρcl, controls the process.

Flashover conditions are sometimes designated with a heat flux to the floor of 20 kW/m^2 (indicative of room smoke layer temperature of 500°C–600°C). So, we see that most thin materials will rapidly ignite under this condition, consistent with our concept of flashover causing the fire to suddenly grow.

4.7.2 Ignition of Thick Materials

An equation similar to Equation 4.2 applies for thick materials (usually $l > 2$ mm). An approximate solution has been determined for a thick material (mathematically done for an infinitely thick solid at a high heat flux) giving

$$t_{ig} \approx \frac{(\pi/4)(k\rho c)(T_{ig} - T_\infty)^2}{\dot{q}_l''^2}, \quad \dot{q}_l'' > CHF \tag{4.3}$$

where k is the thermal conductivity of the material. To make a prediction for a given material, data must be available for the properties in the factor $k\rho c$ (called thermal inertia). In addition, the ignition temperature must be known. In general, k increases in solids as ρ (density) increases. Also k and c increase with temperature. Because the ignition temperatures might range from 200°C to 500°C), k and c should increase considerably during the heating process. In Equation 4.3, a single material value is required for $k\rho c$ at some appropriate average temperature. This value of thermal inertia will typically be higher than that found at ordinary room temperature conditions for that material.

It is remarkable that Equation 4.3 seems to fit a wide range of material data. Typically, these data are derived from measuring the time to ignite under a prescribed constant radiant heat flux. Standard test methods exist for this purpose (e.g., ASTM E-2058[6] and ASTM E-1321[7]). The CHF can be found as the minimum radiant heat flux at which ignition ceases to occur. In applications to follow, and most common in such testing, only piloted ignition is considered. An illustration of a typical analysis of such data in order to obtain the properties needed by Equation 4.3 is shown in Figure 4.11. The CHF was determined at 8 kW/m^2. As the CHF is the heat loss flux at the ignition temperature, a heat transfer calculation can

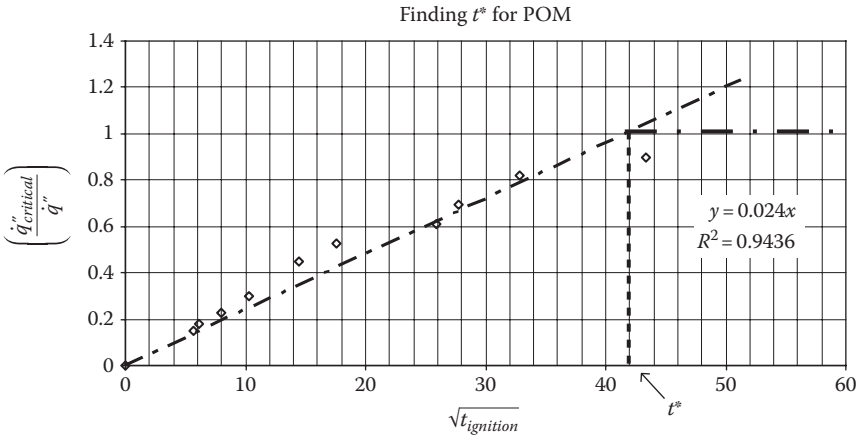

FIGURE 4.11
Ignition data for polyoxymethylene. (From Panagiotou, J. and Quintiere, J.G., Generalizing the flammability of materials, in: *Proceedings of the 10th International Conference on Interflam 2004*, Interscience Communications, London, U.K., 2004, pp. 895–906.)

be made to determine the ignition temperature corresponding to this test condition. In the results to follow for the standard tests, the heat loss conditions are by both radiation and primarily natural convection. We will not go into those details. However, the main point of Figure 4.11 is to indicate how well the data follow the inverse relationship between incident heat flux and square root of the time to ignite as set forth in the approximate theory of Equation 4.3. As the data follow this relationship, the slope of the linear fit to the data can be used to determine the effective kρc for this material. When the incident heat flux equals CHF, as indicated by the value 1 in Figure 4.11, the equation no longer will be applicable. It is noteworthy that just at that condition, the time to ignition (t^*) would be 42^2 or 1764 seconds. This is nearly half an hour or essentially a very long time in an analysis for ignition hazard.

This illustration is typical of ignition data. Plots like this can be used to determine property data needed for Equation 4.3. This is a powerful testing technique to evaluate if a material can ignite and how long it could take.

Some typical piloted ignition times for thick solids are listed in Table 4.2. We see that at 20 kW/m^2, a condition commonly used to imply flashover, it can take one or more minutes to achieve full flaming for common materials. But once higher room thermal conditions are achieved sufficient to ignite other materials, the transition time for full room fire involvement would be much shorter. During the flashover transition, the heat fluxes increase, with the heat fluxes in a room at full involvement attaining as much as 100 kW/m^2. As a result, the increasing heat fluxes reduce the times to ignition or flashover. Our simple formulas, Equations 4.2 and 4.3, do not

TABLE 4.2

Typical Ignition Times of Thick Solids

Heat Flux (kW/m²)	Time (s)	Material
10	300	Plexiglas, polyurethane foam, acrylate carpet
20	70	Wool carpet
20	150	Paper on gypsum board
20	250	Wood particleboard
30	5	Polyisocyanurate foam
30	70	Wool/nylon carpet
30	150	Hardboard

take variable heat flux into account, but we certainly see that increased heat flux reduces the ignition time.

It is commonly observed in flashover that corner edges will ignite before the flat surface of an object. This might be explained in terms of less mass to heat at a corner than a flat surface. In fact, a mathematical solution to heat conduction at the corner edge would give a similar equation to (4.3) except with a constant of $\pi/18$ instead of $\pi/4$. The edge would ignite in about ¼ the time for the same flat surface material.

Typical ignition data are shown in Figure 4.12 for radiant heating of wood particleboard. The ignition times can be shown to agree well with Equation 4.3 ($t \sim (1/\dot{q}_I''^2)$), and at low heat fluxes there is no ignition. The minimum or critical radiant heat flux (CHF) to cause ignition in a long time (greater than 5 minutes in these experiments) is approximately 18 kW/m². Also shown in Figure 4.12 are measured ignition temperatures. These measurements were done with small thermocouples fixed to the wood surface as in Figure 4.13a. The accuracy of the measurement for surface temperature is affected by the way the thermocouple is attached. The scatter shown in the measured ignition temperatures can be expected. A temperature measurement of 350°C ± 50°C is representative of these data. Notice that this measured temperature on the particleboard is very similar to the piloted ignition temperature for redwood heated perpendicular to the grain (see Figure 4.6). The similarity suggests generic data for wood might be used for other wood products. In general, generic data should be used with caution and only for guidance.

If the same experiment were done with direct flame heating as shown in Figure 4.13b,[9] the ignition times do not vary with flame energy (see Figure 4.14). The flame energy, as energy supply rate per width (kW/m) of wood heated, controls the flame height. In other words, the data in Figure 4.14 were derived for various flame heights. The results show, despite variations in flame height, that this flame causes ignition in about 140 seconds (±40 seconds). While there is significant variation, the trend with flame height or flame energy suggests

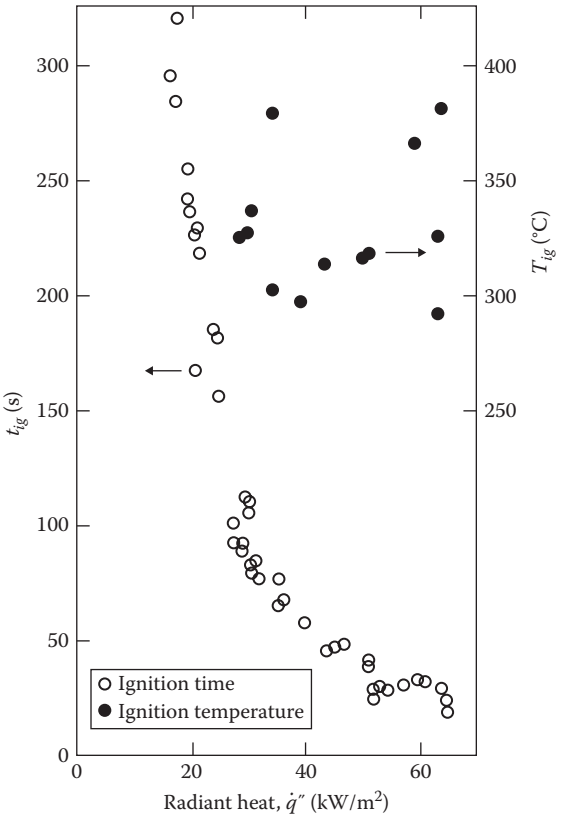

FIGURE 4.12
Measurements of piloted ignition on particleboard. (From Quintiere, J.G., *J. Res. Natl. Bur. Stand.*, 93(1), 61, January–February 1988.)

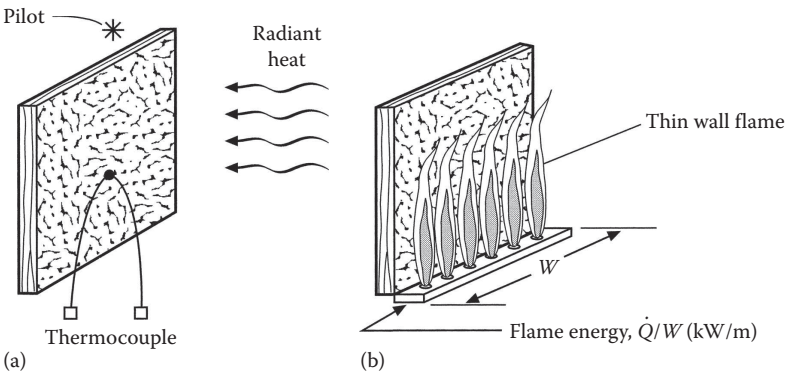

FIGURE 4.13
Ignition experiments: (a) radiant heating and (b) flame heating.

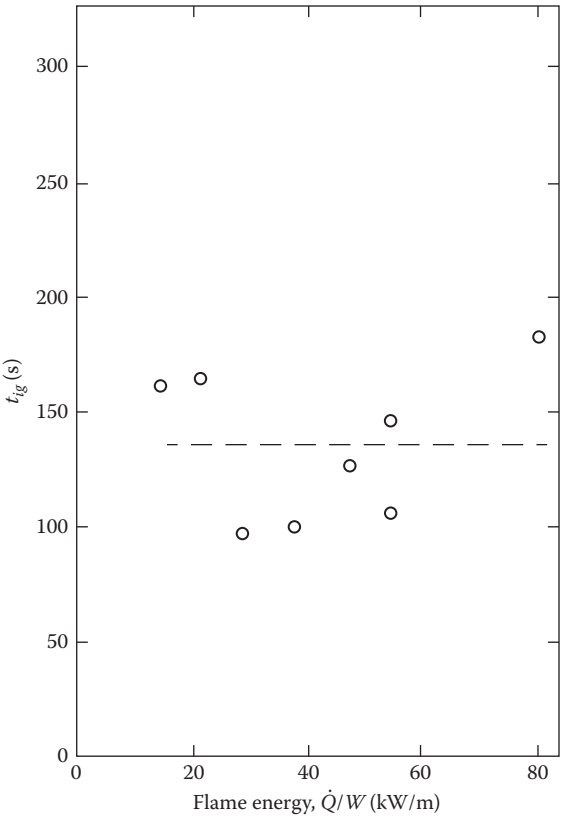

FIGURE 4.14
Measurement of ignition on vertical particleboard by a wall flame. (From Quintiere, J.G., *J. Res. Natl. Bur. Stand.*, 93(1), 61, January–February 1988.)

a relative constant ignition time. Variations can be due to the perception of ignition, the local effects of the flame, and uncontrolled ambient airflow. But if the relative ignition time is agreed to be about a constant, then Equation 4.3 suggests a constant heat flux from the flame. The inferred flame heat flux from Figure 4.12 at 140 ± 40 seconds is approximately 22 ± 3 kW/m^2. This heat flux is typical of turbulent wall flames less than 1–2 m tall. The flux is found to be insensitive to the fuel burned because the flame temperature is nearly independent of the fuel. This experiment with the flame heating related to the radiant heating tests shows the applicability of Equation 4.3 to different heating conditions.

Before leaving this section, let us consider an example using Equations 4.2 and 4.3.

Example 4.2

Determine the time for 1/2 in. thick plywood to ignite subject to a flame heat flux of 25 kW/m^2. If a thin delaminated piece, insulated on the back, with a thickness of 0.5 mm is also heated, determine when it will ignite. Take the initial temperature as 20°C.

Estimated plywood properties:

T_{ig} = 350°C
k = 0.15 × 10^{-3} kW/m-K
ρ = 640 kg/m^3
c = 2.9 kJ/kg-K

Thick case (1/2 in.)

$$t_{ig} \approx \frac{(\pi/4)(k\rho c)(T_{ig} - T_\infty)^2}{\dot{q}''^2_l}$$

$$t_{ig} = \frac{(\pi/4)(0.15\times10^{-3}\ \text{kW/m-K}\times640\ \text{kg/m}^3\times2.9\ \text{kJ/kg-K}\times(350°\text{C}-20°\text{C})^2}{(25\ \text{kW/m}^2)^2}$$

$$t_{ig} = 38.1\ \text{s}$$

Notice this time is lower than the data given for a plywood product shown in Figure 4.17. This difference is an indication of the level of accuracy in generic calculations, as all plywoods are not the same.

Thin case (0.5 mm)

$$t_{ig} \approx \frac{\rho c l(T_{ig} - T_\infty)}{\dot{q}''_l}$$

$$t_{ig} = \frac{640\ \text{kg/m}^3\times2.9\ \text{kJ/kg-K}\times0.5\times10^{-3}\times(350°\text{C}-20°\text{C})}{25\ \text{kW/m}^2}$$

$$t_{ig} = 12.2\text{s}$$

We see the time is much smaller in the thin case than in the thick case due to less mass being heated.

4.8 Solid Properties for Piloted Ignition

A collection of piloted ignition data for thick materials is shown in Figures 4.15 through 4.18. These results were taken by Harkleroad[10] in an early application of Equation 4.3 to derive properties by the technique illustrated in

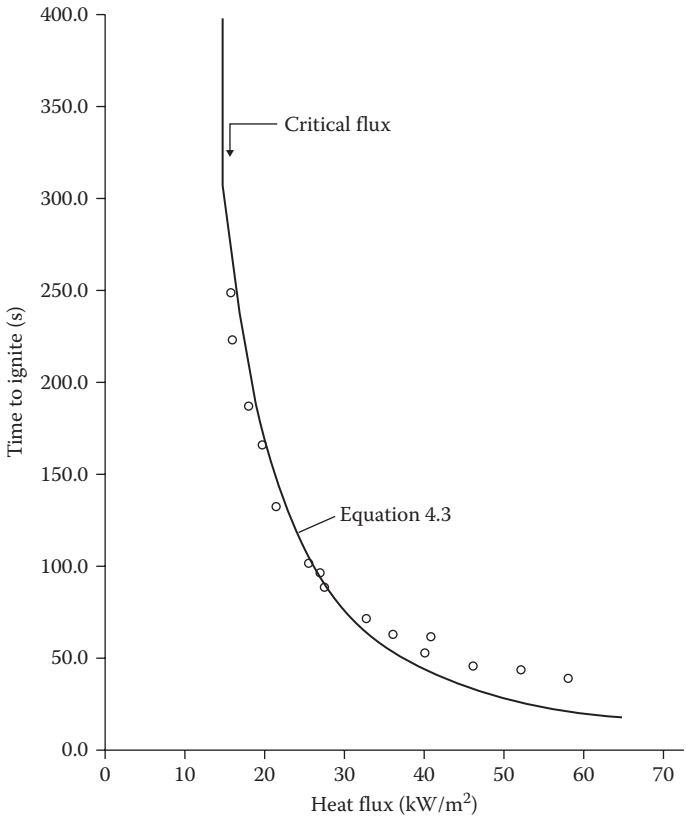

FIGURE 4.15
Radiant ignition times of an asphalt shingle. (From Quintiere, J.G. and Harkleroad, M., New concepts for measuring flame spread properties, NBSIR 84-2943, National Bureau of Standards, Gaithersburg, MD, November 1984.)

Figure 4.11. In Equation 4.3, the properties $k\rho c$ and T_{ig} can only be viewed as effective properties. But by their results, these effective properties give a very good fit to the data in Figures 4.15 through 4.18. Moreover, the materials depicted there are complex materials: an asphalt shingle, paper on gypsum board, plastic foam, and a wood product. The CHF for piloted ignition is also shown in the figures, and it was found by locating the heat flux where ignition would just not occur. This value would depend on how much time was allowed. For practical purposes generally this would not exceed 10–20 minutes, although the experimenter in Figure 4.7 waited for more than 30 minutes. From the CHF, an estimate of the ignition temperature can be found by a heat transfer analysis. In general, the CHF would depend on the convective heat loss. If a wind were present, the CFH would have been higher than the CFH determined here for essentially natural convection conditions. In the event that there is direct flame heating, the CHF would be lower than

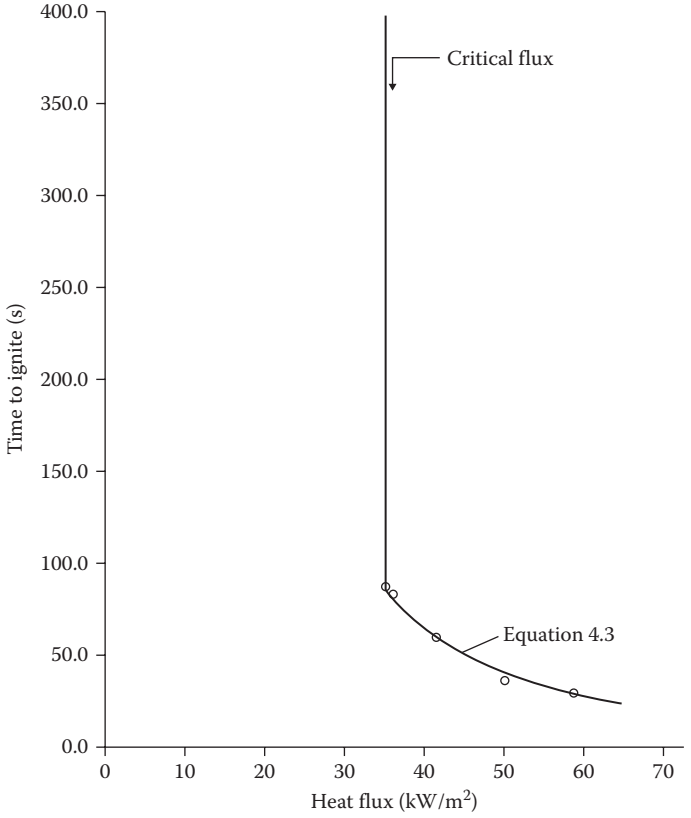

FIGURE 4.16
Radiant ignition times of 1.27 cm gypsum board. (From Quintiere, J.G. and Harkleroad, M., New concepts for measuring flame spread properties, NBSIR 84-2943, National Bureau of Standards, Gaithersburg, MD, November 1984.)

that given in Table 4.3, as only surface radiation heat loss applies. In a confined space, the CHF could be as low as zero.

In Equation 4.3, it is obvious that the numerator involves a set of properties. Tewarson[11] grouped this set into one term: the thermal response parameter (TRP). The TRP is a material property. In this form, Equation 4.3 is written more simply as

$$t_{ig} \approx \left(\frac{TRP}{\dot{q}''_I} \right)^2, \quad \dot{q}''_I > CHF \tag{4.4}$$

where $TRP = [(\pi/4)(k\rho c)]^{1/2}(T_{ig} - T_\infty)$.

Table 4.3 gives data for a wide range of materials in terms of TRP, CHF, and an estimate of the ignition temperature.[8,11,12] These have been generally

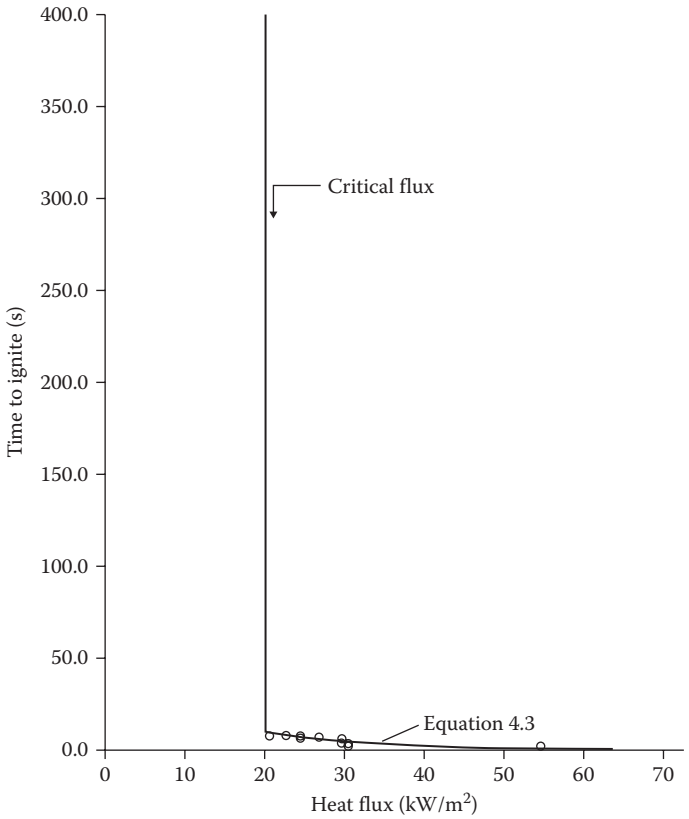

FIGURE 4.17
Radiant ignition times of 2.54 cm rigid foam plastic, polyurethane. (From Quintiere, J.G. and Harkleroad, M., New concepts for measuring flame spread properties, NBSIR 84-2943, National Bureau of Standards, Gaithersburg, MD, November 1984.)

derived from standard test methods such as ASTM E-1321 and ASTM E-2058. The CHF data by these tests apply to a convective heat loss coefficient of about 10–15 W/m^2-K. Usually, the ignition temperature was estimated from the CHF. The data show that the CHF can range from about 10 to 45 kW/m^2 and that the TRP values can range from 60 to 600 kW/m^2-s$^{1/2}$. As the TRP is squared in finding the time to ignition by Equation 4.4, the time to ignition can vary significantly for a given heat flux. The heat flux for flames might range from 20 to 60 kW/m^2 for small to large turbulent flames, respectively, with small laminar candle-like flames on the high end. In general, precise knowledge of the incident heat flux is needed for accurate results. Moreover, specific data are needed for a material considered. The data in Table 4.3 can only be regarded as generic. Indeed, even for the same polymer, results can vary. This is most likely due to the fact that a defined polymer can have other minor ingredients and can vary with processing. Melting materials can also

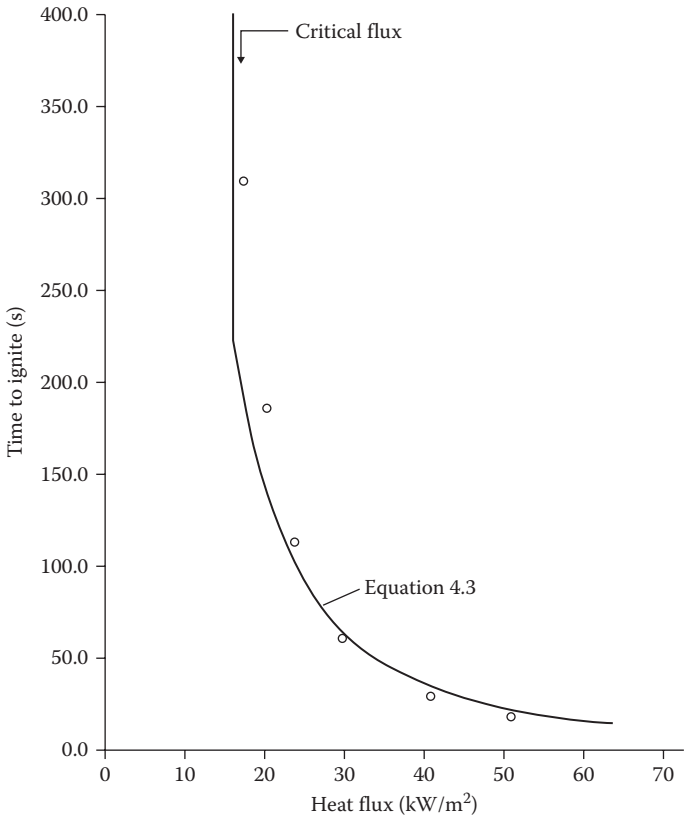

FIGURE 4.18
Radiant ignition times of 1.27 cm plywood. (From Quintiere, J.G. and Harkleroad, M., New concepts for measuring flame spread properties, NBSIR 84-2943, National Bureau of Standards, Gaithersburg, MD, November 1984.)

affect the test result, as in the case of foam plastics, because they can withdraw from the heat source. This can lead results that may not conform to a material's real properties. For example, the decomposition temperature of polystyrene is about 360°C, but there is an entry for polystyrene in Table 4.3 with as estimated ignition temperature of 630°C. This is due to the addition of fire retardants or the behavior of the melting polymer in the test. So, some caution needs to be executed in applying the data. Nevertheless, the test process and the consistency of the data in generating the data of Table 4.3 are sound and offer effective properties that can be used in Equation 4.4 for making estimates of ignition in other heating applications.

To further facilitate the use of Equation 4.4, Figure 4.19 shows a plot of the time to ignition for a range of TRP values. The graph is in semilogarithm form to allow ease in discerning ignition times that can range from 1 to 1000 seconds. Note that in applying the graph, the CHF must be known.

TABLE 4.3

Ignition Properties of Materials

Material	CHF[a] (kW/m²)	T_{ig} (°C)	TRP (kW/m²-s$^{1/2}$)
Ordinary polymers			
ABS, acrylonitrile–butadiene–styrene	12	—	340
PE, polyethylene	15	443	454
HDPE, high-density polyethylene	16	—	260
PP, polypropylene	15	443	288
	15	443	323
	10	274	277
	15	443	333
PVC, polyvinylchloride	10	374	215
	20	—	390
HIPS, high-impact polystyrene	16	—	320
Nylon 66, polyamide	18	—	250
PMMA, polymethylmethacrylate	10	374	274
	8	—	330
	15	378	316
	9	278	196
POM, polyoxymethylene	10	374	250
	8	—	320
SMC ester	20	497	483
High-temperature advanced-engineered polymers			
PSF, polysulfone	30	580	469
PEEK, polyetheretherketone	30	580	550
PC, polycarbonate	20	497	357
	20	580	434
	30	580	455
	30	540	455
PEI, polyetherimide	25	540	435
Highly halogenated advanced-engineered polymers			
PTFE, polytetrafluoroethylene	50	700	654
FEP, perfluoroethylene–propylene	50	700	680
ETFE, ethylene–tetrafluoroethylene	25	540	481
PCTFE, polychlorotrifluoroethylene	30	580	460
ECTFE, ethylenechlorotrifluoroethylene	38	613	450
PVDF, polyvinylidenefluoride	40	643	506
CPVC, chlorinated PVC	40	643	435
Foams and expanded elastomers			
ABS-PVC	19	487	73
PVC	10	374	263
PU, polyurethane foam, rigid	20	435	63
PU, foam, flexible	16	390	183
PS, polystyrene	46	630	331
PS	20	497	146

(*Continued*)

TABLE 4.3 (*Continued*)

Ignition Properties of Materials

Material	CHF[a] (kW/m^2)	T_{ig} (°C)	TRP (kW/m^2-s$^{1/2}$)
Fabrics and woven products			
PET, polyethyleneteraphthalate	10	374	174
Nylon 6	20	497	154
Carpet, wool	23	465	129
	20	435	182
Carpet, wool, treated	22	455	187
Carpet, wool–nylon blend	18	412	283
Carpet, acrylic	10	300	158
Wood and wood products			
Redwood	13	375	145
Red oak	—	304	248
Douglas fir	12	384	159
Maple	12	354	239
Massive timber, varnished	<20	—	197
Plywood	16	390	219
	16	390	238
	<20	—	187
Plywood, FR (fire retarded)	44	620	460
	22	—	131
Hardboard	10	298	331
	14	365	283
Hardboard, gloss paint	17	400	367
Hardboard, nitrocellulose paint	17	400	295
Particleboard	18	412	331
	16	382	307
Fiber insulation board	14	355	198
Composites			
Paper of gypsum board	35	565	321
Paper of gypsum board, FR	28	510	272
Gypsum board with wall paper	18	412	259
Roof shingle, asphalt	15	378	262
Glass-reinforced polyester	16	390	183
	17	400	282
Interior aircraft wall panel, epoxy fiberite	28	505	208

Sources: From Panagiotou, J. and Quintiere, J.G., Generalizing the flammability of materials, in: *Proceedings of the 10th International Conference on Interflam 2004*, Interscience Communications, London, U.K., 2004, pp. 895–906; Tewarson, A., Flammability of polymers, Chap. 11, in: Andrady, A.L., ed., *Plastics and the Environment*, John Wiley & Sons Inc., Hoboken, NJ, 2003; Dillon, S.E. et al., Determination of properties and the prediction of the energy release rate of materials in the ISO 9705 room-corner test, NIST-GCR-98-753, NIST, Gaithersburg, MD, June 1998.

[a] CHF based on natural convective, heat transfer coefficient ~ 10–15 W/m^2-K.

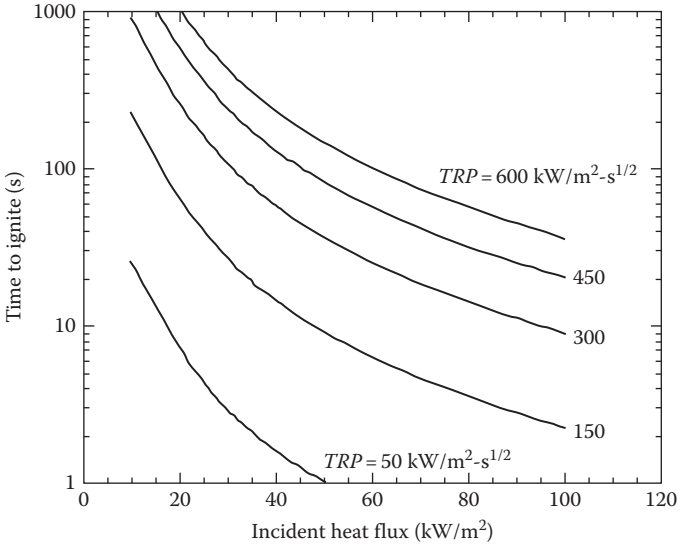

FIGURE 4.19
Graph to estimate time to ignition from TRP.

For example, ECTFE has a CHF of 38 kW/m^2, so the curve labeled with a TRP of 450 can only be used above this CHF for ECTFE. Its time to ignite just above this CHF is more than 100 seconds—a relatively long time for this high-temperature polymer.

4.9 Summary

Ignition to a flame for solid and liquid fuels begins with a mixture of the gasified fuel in air. At the correct concentration of fuel vapor, the mixture can propagate a flame at the LFL with a small energy source (pilot) or at a sufficient temperature alone (autoignition). With a pilot ignition, the flame begins as a premixed flame. The temperature of a liquid to cause this propagating premixed flame is called the flashpoint. At a slightly higher temperature, a diffusion flame can be sustained on the liquid. This is called the fire point. These temperatures lead to the concept of an ignition temperature for materials in general. The CHF needed for ignition just allows the ignition temperature to result from heating.

The vaporization process for liquids is evaporation, while solids must thermally decompose (pyrolysis). Both of these processes increase with temperature. At a critical temperature, the vapor composition is sufficient to form a flame. This can occur with a pilot or alone due to the temperature and

concentration. The latter is autoignition. In a solid, ignition to smoldering likely precedes autoignition.

Two approximate formulas were presented to predict the time to ignition of solids. These apply to a known heat flux incident on a thin (paper, fabric, etc.) or thick solid at a heat flux above the critical value. The thin case involves the product ρcl, while the thick case involves the product $k\rho c$. These comprise the following thermal properties:

ρ = density
c = specific heat
k = thermal conductivity
l = thickness

For thick solids, the TRP was introduced as a convenient grouped property. It facilitated a simple formula for the prediction of ignition time in solids.

Review Questions

1. A laminar match flame imparts roughly 60 kW/m^2 to a surface it contacts. How long would it take Douglas-fir particleboard (Table 4.3) to ignite under these conditions?
2. A small wastebasket fire in the corner against wood paneling imparts a heat flux of 40 kW/m^2 from the flame. The paneling is painted hardboard (Table 4.3). How long will it take to ignite the paneling?
3. The AIT of liquids is usually much lower than that needed to ignite the liquid by a hot surface. Try to explain this difference.
4. Does wood ignite much differently from melting plastics? Explain.
5. What is the CHF needed to ignite redwood to smoldering and to autoignition and piloted ignition?

True or False

1. Thin objects usually ignite more easily than thick objects.
2. Liquid fuels ignite at their boiling point.
3. Thick objects are more difficult to ignite as the material's density is increased.
4. Ignition temperature can be precisely measured for solid fuels.
5. Sunlight magnified 15 times could ignite thin paper.

6. A lit cigarette can ignite gasoline flammable vapors.
7. The flashpoint is the temperature of a solid at autoignition.
8. The boiling point is the maximum temperature of a liquid.
9. When a liquid is fully burning, its surface is likely at the boiling point.
10. Evaporation of water stops at an RH of 100%.

Activities

All of these experiments must be done with safety precautions and with a fire extinguisher available.

1. Use an electric space heater to ignite pieces of newsprint. Find the distance from the heater where autoignition will just occur. By locating a lit match above the paper strip, record the time for piloted ignition to occur at the same location. Explain the results.
2. Experiment igniting small (very small, half dollar size) dishes of liquid fuels. Use ethanol or methanol and note its ease of ignition with a match flame. Cool the alcohol in a bath of ice water and see if it still ignites. Try igniting kerosene in the same way. Explain the results.
3. Try igniting a thick piece of wood (2 × 4) with a match flame. Does it ignite? Or, does it not spread a flame? Observe carefully. Are the corners or edges easier to ignite? Explain the results.
4. Place a thin index card above a candle flame. Investigate ignition without the flame touching the card. Does the card ignite to a flame or smolder? (This experiment must be done with caution and not manually holding the card.)

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5

Flame Spread

Learning Objectives

Upon completion of this chapter, you should be able to

- Describe the different types of fire spread
- Explain flame spread theory in terms of distance heated and ignition time
- Compute flame spread speeds on solids for different cases, given the data
- Describe fire spread rates for many conditions

5.1 Introduction

Ignition occurs in the fuel–gas air mixture. Following ignition, the next step in fire growth is surface flame spread. Of course, the propagation of flame through the gas mixture is a form of flame spread, but we are principally concerned with *surface* spread in this chapter. Such spread involves the participation of the liquid or solid fuel. The surface must reach its ignition temperature to allow its vaporization or pyrolysis region to grow. The perimeter of its vaporization region defines the flame front.

Flame spread requires certain conditions. Among them, principally, is the need for sufficient heat transfer. In general, spread does not always occur; so, the label *non-self-propagating* has commonly been applied to materials after testing. However, just because they are nonpropagating in a particular test does not mean they will not propagate under other initiation conditions. Such labels have been deceptive and often prove harmful to victims of fire accidents. Many tests examine the ability of a material to spread or burn.

One cannot extrapolate from these tests the way a material might spread in conditions of your fire scenario.

This chapter examines the theory of flame spread in terms of its significant phenomena. This information can then be used to explain flame spread in your scenario and perhaps estimate its speed of growth. We will explain how a flame can spread over fuel surfaces or through a porous fuel matrix such as forest brush. Also, fire can propagate through solids as a smoldering process. Although theory and formulas are presented here, these are difficult to use in practical applications because the relevant heat flux and needed material properties are not precisely known. However, we will try to give a basis to making estimations, and in that process, a quantitative evaluation might be performed. In the least, we will try to impart a typical level of fire spread speed to the various types of spread that can occur.

5.2 Definitions

Flame spread is a process in which the perimeter of the fire vaporization region grows. It could even include the process of remote ignitions, if those ignition processes are continual. An example of remote ignitions is the process of firebrands igniting material ahead of a forest fire. Examples of surface flame spread for a solid or liquid fuel can be seen in many fires. Specifically, we mean the extension of the burning region. It is not the flame extent embraced in this definition, but the region volatilizing and supplying the fuel. In general, *fire growth* applies to the increase in the combustion process including surface flame spread, smoldering, and even the expanding fire front in premixed flame propagation.

In flame spread, and in fire growth generally, gravitational and wind effects are important. The flow resulting from the fire's buoyancy or the natural wind of the atmosphere can assist (**wind-aided**) or oppose (**opposed-flow**) flame spread. Figure 5.1 depicts these modes of flame spread. Wind-aided spread occurs in the flame direction of the airflow, while opposed-flow flame spread is opposite to the flow direction. As seen in the figures, the potential for the flame to heat the material ahead of it is very dependent on the flow. This heat transfer is critical.

The flame spread velocity is defined as the rate of motion for the perimeter position x_p in Figure 5.1. The x_p denotes the extent of the **pyrolysis** or vaporization region. Behind the spreading pyrolysis perimeter, there is likely to be another perimeter in which flaming or combustion has ceased. The region between these two fronts (spread and burnout) defines the principal flaming or pyrolysis region. Figure 5.2 shows the burnout and flame fronts for a flame spreading on a thin horizontal stick. The rate of combustion of the vaporizing fuel gases from this region we define as the burning rate. We will see in

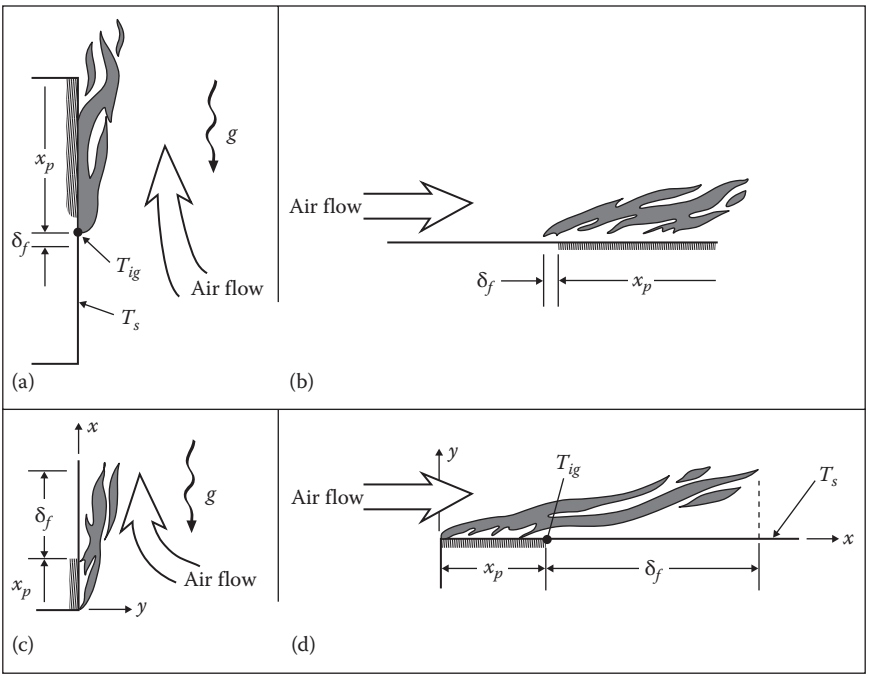

FIGURE 5.1
Flame spread modes. (a) *Natural*: flow is induced solely by the buoyancy of the flame. (b) *Forced*: flow is caused by the ambient wind or a fan. (c) *Opposed-flow* refers to the flames spread opposite to the airflow. (d) *Wind aided* refers to flame spread in the same direction as the airflow.

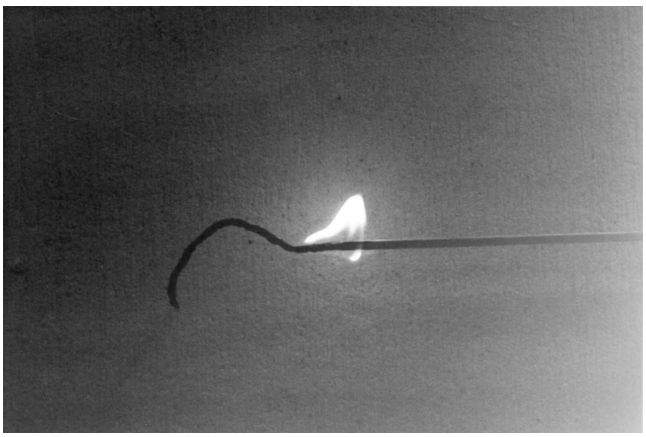

FIGURE 5.2
Flame and burnout fronts on a wooden stick.

Chapters 6 through 8 that the burning rate is directly connected to energy and species produced in a fire. Furthermore, it is significant in establishing the temperature, visibility, toxicity, and corrosivity of the fire. For this reason, flame spread controls the extent of the fire and its burning rate. It plays an important role in establishing the hazard in fire.

5.3 General Flame Spread Theory

The concept of an ignition temperature is key to explaining flame spread in simple, but physically correct, terms. For the process of flame spread, the pilot ignition temperature would apply because a pilot (the flame itself) is always present. If we examine Figure 5.1 again, we can label the position x_p at the ignition temperature, T_{ig}. The temperature further ahead of the flame, not affected by direct heating from the flame, is labeled T_s. The distance along the surface affected by the flame's heat transfer is labeled δ_f. In general, the flames can heat this region ahead in many ways. These depend on the mode of spread—natural, forced, opposed, or wind-aided—and on the nature of the solid or liquid fuel. Symbolically, this process is illustrated in Figure 5.3. The illustration depicts steady flame spread. An observer *riding* on the flame front, at position x_p sees the new fuel coming toward it at the flame spread velocity, V. In other words, if the flame front is stationary according to the observer, it appears that the new material to burn is flowing toward the observer at the flame speed, V, and into the region burning behind the observer. The general flame spread velocity formula states that the rate of energy supplied to this newly heated fuel, bringing it to ignition temperature T_{ig}, is equal to the net heat transfer rate from the burning region, $\dot{q}$. Hence, we have an energy balance for spread to occur.

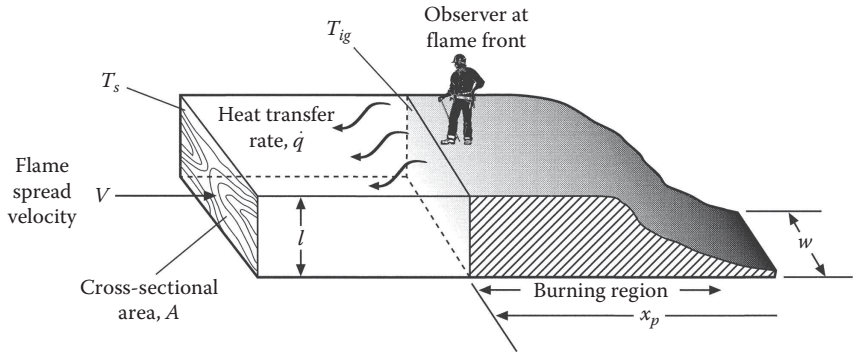

FIGURE 5.3
Flame spread model.

[Rate of energy required] = [Rate of heat supplied]

$$\rho VAc(T_{ig} - T_s) = \dot{q}\ (\text{kW}) \tag{5.1}$$

where

ρ is the fuel density, kg/m^3
c is the fuel-specific heat, kJ/kg-K
A is the cross-sectional area, wl, m^2
T_s is the fuel temperature beyond the range of the flame's heat, °C

The formula is a bit complicated for those new to this type of math and science. Let us talk our way through it. On the right-hand side is the heat flow rate needed for the spread in kW. This heat rate must be capable of heating the new material to its ignition temperature (flash-point). On the left-hand side, we have the flow rate of a new material taken up to the ignition temperature from its original value. If we combine all of the quantities together in terms of their units, the left-hand side has units that emerge as

$$\frac{\text{kg}}{\text{m}^3}\frac{\text{m}}{\text{s}}\text{m}^2\frac{\text{kJ}}{\text{kg-K}}\text{K} = \frac{\text{kJ}}{\text{s}} \equiv \text{kW}$$

This is the energy flow rate of the spread material that must be equal to the heat flow rate from the flame (kW). We have applied a conservation of energy principle. It must be obeyed if flame spread is to occur. Too little heat, no spread will occur. Too high an ignition temperature, slow or no spread may result.

The flame spread velocity is obtained as

$$V = \frac{\dot{q}}{\rho cA(T_{ig} - T_s)} \tag{5.2}$$

Many specific cases of flame spread can be derived from this formula by more carefully describing $\dot{q}$ and A. We will consider some approximate formulas that follow from Equation 5.2. These formulas are in agreement with more complex analyses beyond the scope of this text. There are approximate formulas that should be considered as tools for making estimates, with accurate results subject to assumptions. Again, orientation, wind, and the nature of the fuel all make a difference.

5.4 Spread on Solid Surfaces

For spread over solid surfaces, it has been shown that the most significant heat transfer rate is at the surface over a length δ_f, as shown in Figure 5.1. Heat flow rate is the product of heat flux and the surface area it acts on. Therefore,

$$\dot{q} = \dot{q}''\delta_f w \tag{5.3}$$

where
$\dot{q}''$ is the flame forward heat flux
w is the width of the fuel as shown in Figure 5.3

The flow area is normal to the surface area, and it is designated as A or wl, where l is the fuel's thickness. Here, we are making a simplification, as we are implicitly assuming that the heat is uniformly distributed over the thickness, and a uniform temperature results in depth. This will not be a restrictive assumption, and other results to follow will be more general.

If we substitute these formulas into Equation 5.2, we obtain

$$V = \frac{\dot{q}''\delta_f}{\rho c l(T_{ig} - T_s)} \tag{5.4}$$

Again, referring to Figure 5.1, V is the rate of movement of position x_p. Orientation and natural flow or forced flow conditions affect the heating distance δ_f and the associated flame heat flux $\dot{q}''$. Measurements have shown that for downward spread on a wall, the dominant heat flux extends over a δ_f of approximately 1 mm. It can be as high as 70 kW/m^2. For upward flame spread on a wall, the heat flux is generally 25 kW/m^2 (fairly constant with ±5 kW/m^2 for flames extending above the vaporizing region in distances from 0.20 to about 2 m). Here, the flame extension is the luminous flame region that approximates δ_f. These heat flux results appear to be independent of the wall fuel; so, whether we have a gasoline saturated wood wall, or the wood wall itself, the incipient heat flux from the flame to the wall is up to 70 kW/m^2 going down against the flow of air, or about 25 kW/m^2 going up. The downward flame is a laminar and premixed flame at its front, and the upward flame will shortly become turbulent. The tendency for these heat fluxes to not strongly depend on fuel type is due to the invariance of flame temperature in air for most common materials.

5.4.1 Effect of Thickness

Just as for the ignition of solids, we must distinguish between thick and thin solids in flame spread. In the form of Equation 5.4, the result is strictly for the thin material, as the temperatures are uniform in depth. In general, for a thick material, the surface heat transfer from the flames can only penetrate to a certain depth. This heating in depth takes place during the time to heat the surface from its original temperature T_s to the ignition temperature T_{ig}. This heating time is, in fact, the ignition time (t_{ig}) caused by the heat flux of the spreading flame. From our discussion on heat conduction in Chapter 3, the actual depth heated in this time is related to $\sqrt{(\alpha t_{ig})}$, where α is the thermal diffusivity, $k/\rho c$. So, if the actual thickness of the material is greater than this heated depth in flame spread, the thickness of the material is inconsequential in the flame spread process. In other words, the material is thermally thick and the spread rate is not dependent on its thickness. While this heating depth depends also on the heat flux, generally for flame spread heat fluxes, materials less than 2 mm can be approximated as thin.

For a thin solid (l < 2 mm), the ignition time, t_{ig}, is given by Equation 4.2, which allows us to write Equation 5.4 as

$$V = \frac{\delta_f}{t_{ig}} \tag{5.5}$$

since the thin solid ignition time is

$$t_{ig} = \frac{\rho c l (T_{ig} - T_s)}{\dot{q}''}$$

This is a remarkably simple equation, as it says that the speed of the flame spread on the surface is the distance heated by the flame divided by the time to ignite that new material. This is akin to computing your average speed over a distance traveled.

Indeed, the same Equation 5.5 holds for the thick material (greater than about 2 mm). For a thick solid, the entire thickness l is not heated during the ignition time. Recall that the ignition time for a thick material is given by

$$t_{ig} = \frac{\pi}{4} k \rho c \left[\frac{T_{ig} - T_s}{\dot{q}''} \right]^2$$

The spread velocity for the thick solid is given by Equation 5.5 with this thick solid ignition time. Most flame spread problems can be put into the form of Equation 5.5. The solution then depends on determining the heating length δ_f and the ignition t_{ig} caused by the flame heat transfer.

Composite materials, such as plasterboard with a paper face, should be regarded as a single *thick* material in determining ignition and spread. Although the paper on the plasterboard may be physically thin ($l < 2$ mm), the combination of the paper and plaster acts as a *thick* material, because flame heat transfer from the paper burning will be conducted into the plaster. However, if the paper delaminates, then it can ignite and spread as a thin material. Such physical effects of delaminating, melting, and so on will impact the heat flux ahead of the flame, and the distance the heating is felt. Empirical results from standard tests are likely to contain these complex physical effects, but the form of their results is usually inadequate to use in the prediction of spread.

5.4.2 Downward or Lateral Wall Spread on a Thick Material

For downward or lateral flame spread on a wall surface, the combination of the δ_f and $\dot{q}''$, that is, $(\dot{q}'')^2\delta_f$, for thick solids, depends on the air flow and on the way the fuel behaves. In other words, the physical effects in spreading against the airflow can modify the heat flow and distance in which it acts ahead of the flame. For such spread in still air, this combination has been found to depend only on the fuel and can be considered a fuel-flame spread property. This property is designated by ϕ in the following formula:

$$V = \frac{\phi}{k\rho c(T_{ig} - T_s)^2} \tag{5.6}$$

where

$$\phi = \frac{4}{\pi}\dot{q}''^2\delta_f$$

This equation follows by applying Equation 5.5 to a thermally thick material.

Up to now, no restriction has been put on the flame spread formula. Should it always hold? We know materials do not spread if the heating conditions are not sufficient. A measure of this is the initial temperature of the material. This type of opposed-flow flame spread will only occur if the surface temperature is above a critical value. Such data can be obtained for materials from **ASTM E-1321**: Standard Test Method for Determining Ignition and Flame Spread Properties.[1] The test measures conditions for lateral spread on a vertical sample. However, similar results apply to downward or horizontal spread, as the flow conditions into the spreading flame would be similar.

Figure 5.4 shows a typical example of the type of surface flame spread found in this test. Below the minimum temperature for spread, 120°C, no spread occurs. Above this temperature, spread occurs at increasing velocity as the surface temperature is increased. This temperature occurs in the

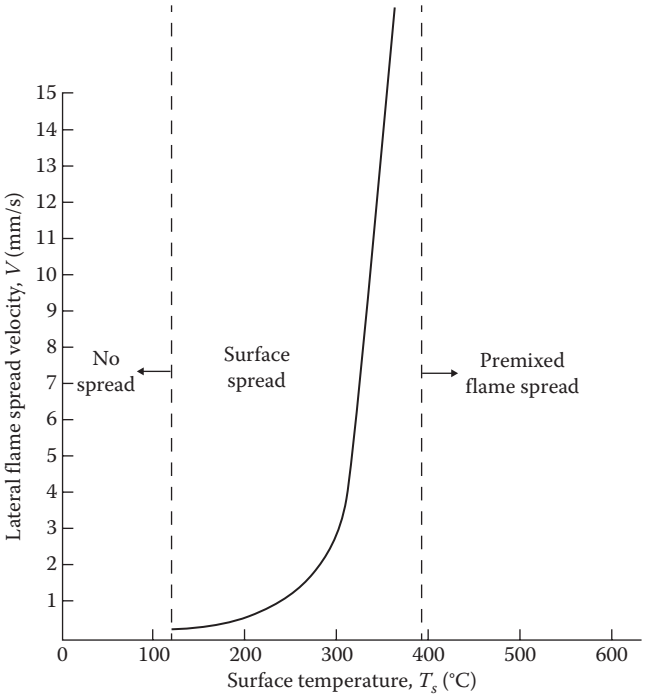

FIGURE 5.4
Lateral flame spread based on the test of plywood in still air.

ASTM E-1321 test by heat from an inclined external radiant panel burner. The test actually imposes a decreasing surface temperature as the flame spreads into the material, and accordingly, the flame slows down as T_s decreases and the ignition time increases. In actual fire conditions, this radiant heat transfer occurs from the hot smoke contained in a room. In that case, the flame spread can accelerate as the room heats. The flame heats a very small region (~1 mm) ahead of the lateral or downward spreading front. The smoke, in contrast, heats the wall to temperatures (T_s). The level of heating depends on the energy release rate of the fire. As this surface temperature increases, the surface flame can now heat the wall close to the flame to the ignition temperature (390°C) more quickly.

Suppose a fire occurs in a room with the plywood wall shown in Figure 5.4. At some point, the fire has sufficient heat flux (above the critical heat flux for ignition) to ignite the plywood. In order for lateral or downward flame spread to occur, the room fire conditions must heat the plywood to 120°C, its minimum temperature for spread. Here, the spread rate is only 0.33 mm/s. At T_s = 300°C, it achieves 3 mm/s or about 7 in./min. This is how room fire conditions can accelerate fire spread over all burning objects. Equation 5.6 suggests that when the surface temperature of

TABLE 5.1

Lateral Flame Spread Data from ASTM E-1321

Material	T_{ig} (°C)	$k\rho c$ (kW/m^2 K)^2	ϕ (kW^2/m^3)	$T_{s,\min}$ (°C)
Wood fiberboard	355	0.46	2.3	210
Wood hardboard	365	0.88	11.0	40
Plywood	390	0.54	13.0	120
PMMA	380	1.0	14.4	<90
Flexible foam plastic	390	0.32	11.7	120
Rigid foam plastic	435	0.03	4.1	215
Acrylic carpet	300	0.42	9.9	165
Wallpaper on plasterboard	412	0.57	0.8	240
Asphalt shingle	378	0.70	5.4	140
Glass-reinforced plastic	390	0.32	10.0	80

Source: Quintiere, J.G. and Harkleroad, M., New concepts for measuring flame spread properties, NBSIR 84-2943, National Bureau of Standards, Gaithersburg, MD, November 1984.

the plywood reaches 390°C, its ignition temperature, the speed would be infinitely fast. This result is not correct because the surface spread formula no longer applies at this point. As the plywood reaches its ignition temperature, the pyrolyzed gaseous fuel at the surface would be within its flammable limits. Consequently, the flame would propagate through the gas mixture near the surface with the appropriate premixed flame speed (probably about 30–100 mm/s).

Typical data taken from ASTM E-1321 for lateral flame spread in still air are shown in Table 5.1. These data can be used to construct plots as depicted in Figure 5.4. It should be emphasized that data should not necessarily be generalized to similar materials. For example, all plywood, or polycarbonates may not be the same. Material compositions can vary to a degree; fire retardants may have been included, or composite materials can vary in construction. However, the data of Table 5.1 are generally representative of common construction or interior finish materials. The T_{ig} and $k\rho c$ values for these materials in Table 5.1 would apply to other modes of piloted ignition and flame spread, but the ϕ and $T_{s,\min}$ apply only to the lateral spread conditions in still air. According to Equation 5.6, ϕ can be estimated for well-behaved materials. For these, it is known that the leading premixed flame imparts a level of heat flux of about 60–70 kW/m^2 over about 1 mm of surface. Other materials might delaminate, melt, or distort to affect these numbers. However, using the well-behaved material values, we can compute ϕ:

$$\phi = \frac{4}{\pi}\dot{q}''^2\delta_f = \frac{4}{\pi}(65\ \text{kW/m}^2)^2\delta_f\left(1\ \text{mm} \times \frac{0.001\ \text{m}}{1\ \text{mm}}\right) = 5.38\ \text{kW}^2/\text{m}^3$$

We see that real values in Table 5.1 range from about 1 to 15 kW^2/m^3. These variations between real and ideal give some indication of the accuracy in predicting flame spread from first principles. The derived value of ϕ from the test accounts for real effects not directly modeled. It is an empirical factor. It should be obvious from Equation 5.6 that a larger ϕ means a higher flame spread velocity.

The student should try to recognize the general speeds associated with this type of opposed-flow flame spread in air. It is of the order of about 1–2 mm/s. It can increase as the surface temperature ahead of the flame increases, and it needs a critical minimum surface temperature for spread to occur. A wind into the flame will increase the flame speed because the leading edge convective heat transfer will increase. However, at a high velocity the fuel may not have time to fully react and the flame temperature will drop causing the flame to slow and eventually extinguish. This is called "flame blow-off."

5.4.3 Upward or Wind-Aided Spread on a Thick Material

Flame spread in the direction of the airflow is generally referred to as wind-aided spread. Upward flame spread on a wall or flame spread under a ceiling in still air is also termed *wind-aided*. In these natural convection cases, the *wind* is solely due to the buoyant flow caused by the fire itself. The heat to make the flame move is mainly caused by the heat transfer from the extended luminous flame adjacent to the surface. The flame extends the distance δ_f as shown in Figure 5.1. Unlike opposed-flow spread in which this distance is primarily a constant that depends on the flow, here this distance depends on the extent of burning. We will see in Chapter 7 that flame length depends principally on the energy release rate of the fire driving it. So with increased burning, a longer flame and a higher speed result.

Let us consider the scenario for upward flame spread on a vertical wall as shown in Figure 5.5. An igniting fire, placed adjacent to a wall, "insults" it with a sufficient heat flux to ignite the wall over a heated length x_p. At that point, the combined fuel from the igniting fire and the wall section ignited produce a flame height x_f. The flame extension δ_f is $x_f - x_p$. Our flame spread velocity at the onset of spread is given by Equation 5.5, where the ignition time (t_{ig}) depends on the flame heat flux at that time. As the wall fire continues to spread, it will be less and less dependent on the igniting fire. Indeed, the igniting fire may burn out. Also, the wall may burn out. Both of these extinctions will reduce the height of the flame, x_f. Alternatively, the wall material may contain sufficient fuel (e.g., plywood compared to wallpaper on plasterboard) to cause x_f to continue to increase. If x_f depends directly on x_p, the flame speed will accelerate because x_f outruns x_p.

Suppose x_f was always 50% greater than x_p. Then δ_ϕ would equal $0.5x_p$ and the speed would continue to increase as x_p increases. Take typical plywood with a TRP of about 229 $kW\text{-}s^{1/2}/m^2$ burning with a turbulent flame on a wall (see Equation 4.6 and Table 4.3). Turbulent wall flames,

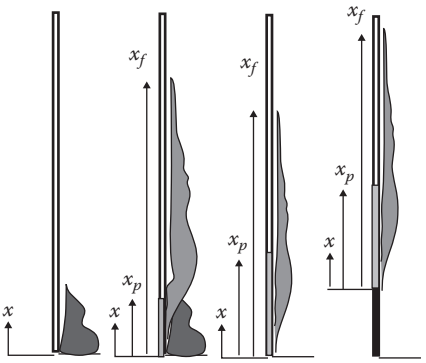

FIGURE 5.5
Sequence of events in upward flame spread.

burning with heights of about 0.2–2 m give a heat flux of about 25 kW/m^2. This gives an ignition time in this flame spread of [(229 kW-s$^{1/2}$/m^2)/25 kW/m^2]^2 or 83.7 seconds. For the 50% flame growth case, according to Equation 5.5 the speed of the wall would be $0.5x_p$/83.7 seconds or about 6 mm/s for a x_p of 1 m. As x_p continues to grow, the speed increases accordingly. Here, we have some appreciation of the magnitude of upward flame spread. More easily ignitable materials than plywood could have a speed 10 times higher. Thin materials that burn out quickly could cause the speed to decrease. Materials with low burning rates may not be able to get a sufficient flame length, and the flame will not propagate. This type of wind-aided spread is more complex than opposed-flow spread. It is generally unsteady, whereas opposed-flow spread is generally constant if it occurs for a given material.

In general, upward or wind-aided flame spread depends on the nature of the igniting fire and the combustion properties of the wall. Of course, if this upward flame spread scenario occurs in a room, the smoke layer will increase T_s causing the surface velocity to also increase as in downward or lateral spread. But unlike downward spread where δ_f is small and nearly constant (~1 mm), for upward spread δ_f can sharply increase or decrease due to combustion and flow properties that affect flame length, x_f. As a result of different flow features, flame spread up a wall, under a ceiling, or driven by airflow in a ventilation duct is all different. Our ability to write perfect formulas for each case is not yet possible, so we are left with only the framework of Equation 5.5 at this time. Unlike the case of opposed-flow spread where δ_f is constant, these wind-aided cases will be unsteady, because δ_f will change as the flame propagates. Spread will accelerate or stop. Typical wind-aided spread rates might range from roughly 1 to 100 cm/s.

5.5 Spread through Porous Solid Arrays

Flame spread can take place through porous solid fuels such as forest brush and debris. Even wind-aided flame spread through the arrays of urban dwellings can be considered in this class of flame spread. Figure 5.6 illustrates this type of spread in still air through a wood crib. In this case, the forward heat flux to cause spread is mainly within the array, not just at the outer surface.

There will be a flame above the porous material, but the principal factor controlling the spread is the heat transfer within. A wind can increase both heating levels. The spread rate is controlled by the fuel mass in the array characterized by the bulk density, ρ_b. The bulk density is the mass of the solid fuel divided by the volume of the entire array—the fuel and the air. Assume again that the fuel elements are thin so that they heat uniformly. From Equation 5.2, for the array we obtain

$$V = \frac{\dot{q}''}{\rho_b c(T_{ig} - T_s)} \tag{5.7}$$

where $\dot{q}''$ represents the overall heat flux within and on top.

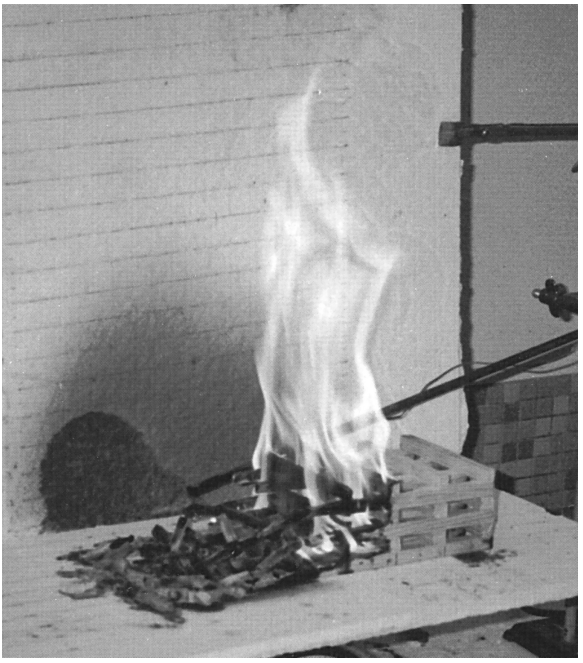

FIGURE 5.6
Flame spread through a porous array—a wood crib.

Most often, this porous array is considered to be composed of cellulosic fuel matter, so that fixes the fuel properties. However, moisture content is a big factor. Equation 5.7 is only symbolic as to implement it requires discriminating the heat fluxes and other effects, such as wind, terrain, and moisture. The forward heat flux in the array is a complex combination of radiation from the fuel elements and convection due to wind effects.

In wildland fires, the U.S. Forest Service uses a model formulated by Rothermel that is qualitatively explained in Reference 4 in which these complexities are discussed. Equation 5.7 forms the basis of the Rothermel model in which more detail is contained with specific data for forest fuels. It is used as a tool in combating forest fires.

Wildland fires are very unique. In many cases, they begin with a lightning strike that leads to smoldering of the forest ground covering dead brush. This can lead to flaming much later, very likely due to a wind. This natural process of burning out the ground forest material is a good thing for a forest. Sometimes, the process is intentional; it is called "prescribed burning." In any case, whether intentional or accidental, the combination of dry forest material and a sustained wind can cause the fire to grow. The wind can push this early ground brush fire to a higher level, and with severe conditions it can lead to burning the live forest materials. It can even get to the top of trees; this is called a "crown fire." Such a fire condition is very bad and nearly impossible to defend against. Now the embers generated as firebrands can travel well ahead of the fire front and cause new fires. With the development of homes built into the forest, the phenomenon of the "urban wildland fire" has become a common event.

Let us address some specific analyses for forest and porous fuel fires that give some quantitative estimate for their spread speed. Roughly, the heat flux and the thermal properties for forest materials are nearly constant. Thomas[5,6] reports results for porous arrays where the flame speed, V, inversely depends primarily on ρ_b. This has been found to hold true for woody elements over a wide range of thicknesses. He reports that for spread in still air:

$$V = \frac{C}{\rho_b} \tag{5.8}$$

where

V is in m/s

ρ_b is in kg/m^3

C is a constant of roughly 0.07 kg/m^2-s for typical wildland fuels and 0.05 kg/m^2-s for wood cribs of sticks up to 3 cm in diameter

In general, C might be regarded to vary as 0.06 ± 0.02 kg/m^2-s.[5,6] This constant contains complex heat flux and fuel property effects. It is remarkable that it varies relatively little between wildland fuels and composed array of sticks.

Wind is a serious factor in forest and urban conflagration fire spread. Indeed, if the wind dies, the ability to contain these fires becomes more realistic. For wind-aided flame spread through porous arrays, Thomas[6] reports a modification to Equation 5.8 as

$$V = \left(\frac{C}{\rho_b}\right)(1 + aV_\infty) \tag{5.9}$$

where
V_∞ is the wind speed
a is a constant ≈ 1 s/m

The wind speed effect on the flame speed is approximated here as linear. In reality, it can be more complex. This formula represents a good first approximation to the effect of wind.

Figures 5.7 and 5.8 show the accuracy of these simple formulas for different porous wood-based fuel arrays. Their comparison is against controlled laboratory data and field data. Figure 5.7 shows that a wide array of data varying in bulk densities from about 20 to 200 kg/m^3 gives an average for C of 0.077 kg/m^2-s. Figure 5.8 shows a trend curve for wildland fuels and two straight trend lines for wood crib data. Equation 5.9 is a good approximation up to a wind speed of about 5 m/s for these fuels, after which the wildland spread rate increases more sharply with wind speed. Urban fire data for conflagrations of Japanese cities are also shown in Figure 5.8 where the bulk density of the dwellings has been taken as 10 kg/m^3 in order to plot the data. The scatter in these real field data can be expected, but their trend is clear. Figure 5.9 shows more recent results of fire spread through the part of Kobe following the Hyogoken Nanbu earthquake of 1995. These data also show scatter as can be expected from the actual organization of the houses. They show leeward speed (in the wind direction, wind-aided), windward (into the wind, opposed), and wind side (normal to the wind direction). We expect the latter two to be similar as they are in the category of opposed-flow spread. If we take the Thomas estimation to be the same for these wooden houses of Kobe (10 kg/m^3), then Equation 5.9 can be used to estimate the earthquake results as

$$V = \frac{C}{\rho_b}(1 + V_\infty) = \frac{0.06\ \text{kg/m}^2\text{s}}{10\ \text{kg/m}^3} \times \frac{3600\ \text{s}}{1\ \text{h}}(1 + V_\infty\ \text{m/s}) = 21.6\frac{\text{m}}{\text{h}}(1 + V_\infty\ \text{m/s})$$

Figure 5.9 shows a fire spread of about 21 m/h upwind of for no wind, surprisingly similar to the estimate. However, at a wind speed of 4 m/s, the fire spread in the wind direction (leeward) is estimated by the formula as 108 m/h compared to the data ranging from about 60 to 80 m/h. Still, not so bad.

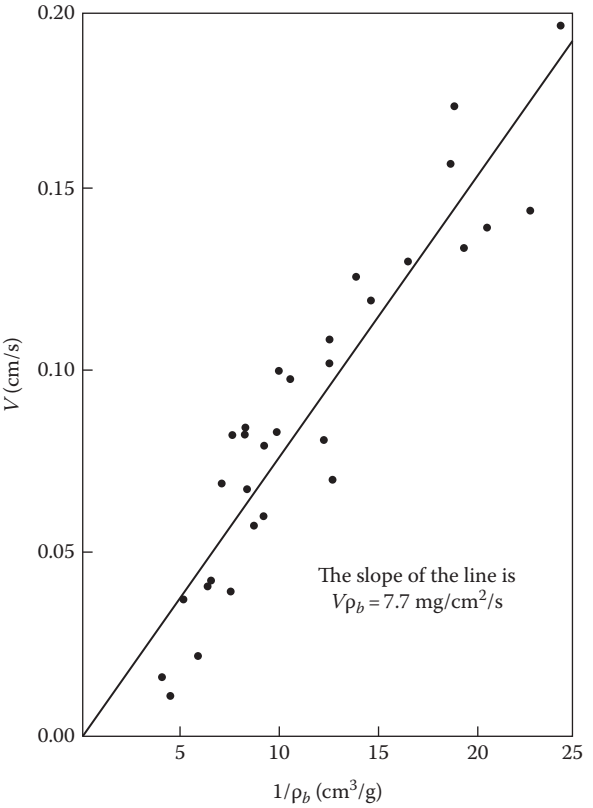

FIGURE 5.7
The effect of bulk density of fire spread in a porous fuel array. (From Thomas, P.H., *Forestry*, 20(2), 139, 1967.)

Recently, Tanaka and coworkers have presented a model to predict the spread in the Kobe postearthquake fires.[8] Their model is based on the mechanism depicted in Figure 5.10.

The model is based on a computer zone model for building compartments. The model was extended to include building-to-building spread. The heat transfer mechanisms that promote spread include

1. Thermal radiation from the building fires
2. Convection from the wind-blown plumes
3. Conduction from the ejected and transported fire brands

The model gave reasonable prediction regarding the number of burnt buildings in a given conflagration area of Kobe. While quite complex in its detail

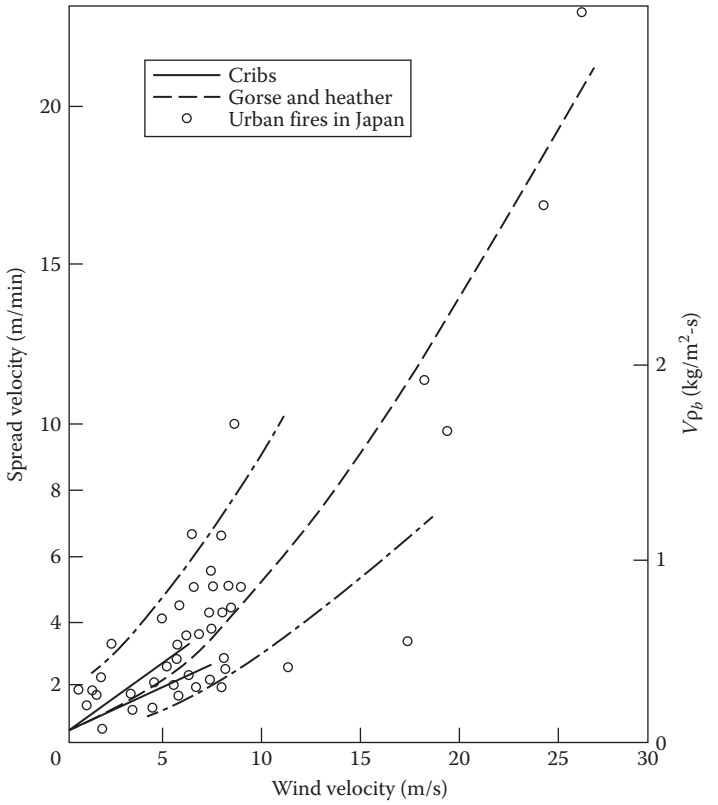

FIGURE 5.8
Comparison of spread rates in porous arrays with the effect of wind. (From Thomas, P.H., *Forestry*, 44(2), 155, 1971.)

and execution, the spread framework follows the basic principle: sufficient heat transfer has to cause the next region to reach its ignition temperature.

5.6 Spread on Liquids

Surface flame spread on liquids is similar to the mechanisms discussed for surface flame on solids. However, the liquid differs in that motion can be induced in the liquid due to the spreading flame. The fact that the surface of the liquid is hotter under the flame than the cooler liquid upstream leads to a buoyant flow that can influence the flame spread process. Also, motion can be induced in the liquid by **viscous** or **surface tension** effects. Surface tension increases as the temperature decreases. So, as one moves ahead of the flame on a liquid surface toward the cooler fluid, the surface tension increases and

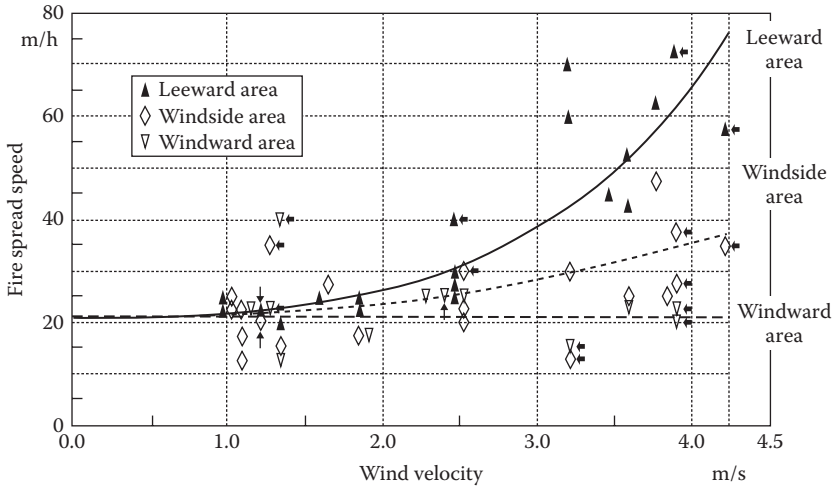

FIGURE 5.9
Wind velocity affecting the flame spread among urban dwellings following the Kobe earthquake. (From Nagano, Y., Fires, in: Kaji, H., ed., Comprehensive study of the Great Hanshin earthquake, UNCRD Research Report Series No. 12, United Nations Centre for Regional Development, Nagoya, Japan, 1995, p. 117.)

pulls the flame forward. This is a distinct difference to that of a solid, and it adds to the flame spread speed caused by heat transfer alone. The surface tension variation with temperature is the chief mechanism that makes liquid surface flame spread different from solids. Here, we are talking about flame spread on a horizontal liquid pool unaided by wind. This surface tension effect would not be a significant mechanism in wind-aided spread on liquid pools because surface flame heat flux would dominate. For flame spread on a liquid pool in still air, the surface tension effect causes significant energy transfer to the liquid ahead of the flame. This liquid energy transfer raises the temperature (T_s) ahead of the flame front, reducing the energy needed for spread. Therefore, from Equation 5.2, the liquid flame spread speed is higher over what we would expect for a solid with comparable properties.

Figure 5.11 shows experimental results of Akita[9] for a 2.6 × 1.0 cm deep pool of methanol. The ignition temperature for methanol is the same as the flashpoint, which is 11°C. At that temperature, a fuel–air mixture exists at the surface that can be ignited by the surface flame. The flame speed results are plotted against the original liquid temperature T_s of the liquid similar to Figure 5.4 for plywood. The results between the plywood and the liquid fuel are distinctly different. The general enhancement of the surface tension motion of the liquid produces a flame speed of greater than 1 cm/s, while for the plywood it is generally about 1 mm/s before T_s nears its ignition temperature. Also, there is a pulsating region that applies to liquid spread. Here, the spread rate can oscillate between the maximum and minimum

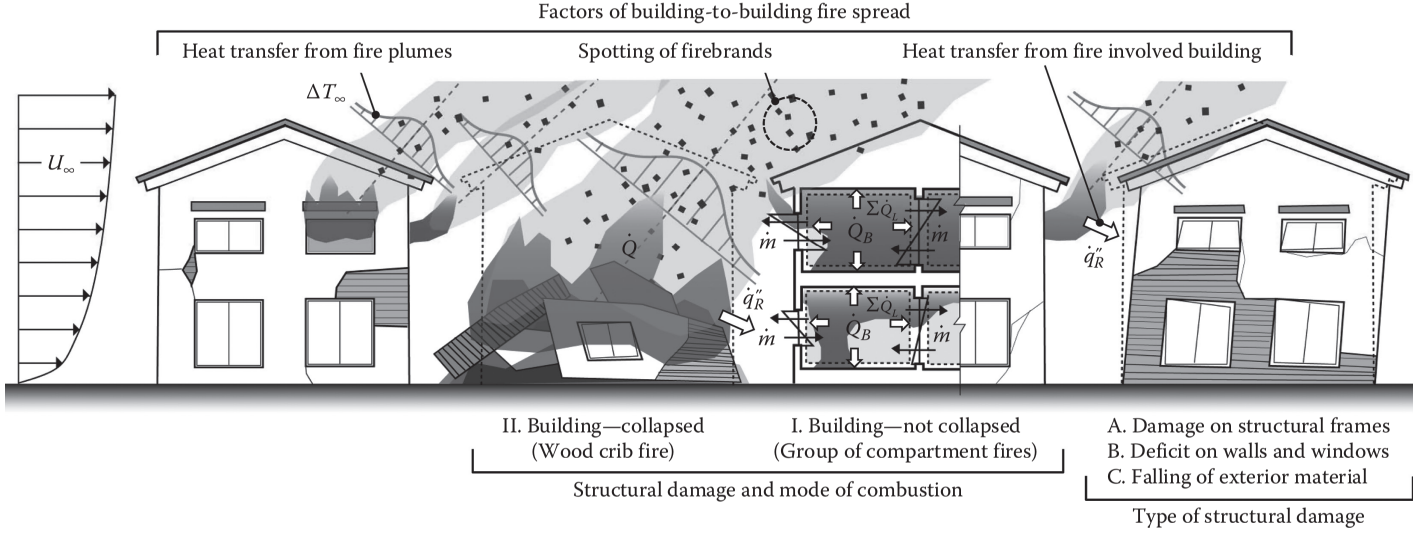

FIGURE 5.10
Mechanisms of post-earthquake spread. (From Himoto, K. et al., A post-earthquake fire spread model considering damage of building components due to seismic motion and heating of fire, in: *Proceedings of the 10th International Symposium on Fire Safety Science*, 2011, pp. 1319–1330.)

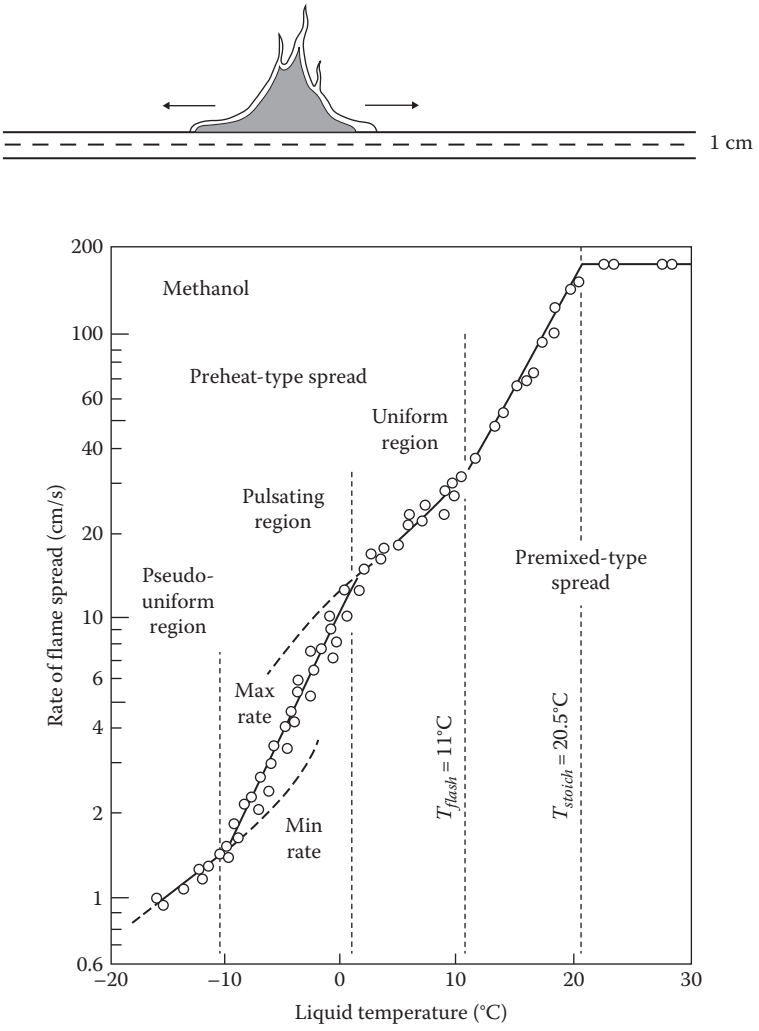

FIGURE 5.11
Rate of spread on a liquid pool of methanol as a function of its temperature. (From Akita, K., Some problems of flame spread along a liquid surface, in: *14th Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1973, p. 1075.)

values shown. For both the plywood and the methanol, as T_s reach their ignition temperature a flammable mixture is reached. In Figure 5.11, the premixed gas-phase velocities are explicitly shown for temperatures above the flashpoint. These range from about 30 to 180 cm/s. Such premixed results were not explicitly shown for the plywood in Figure 5.4.

The discussion here has been for pools of liquid that have a considerable depth. A liquid spilled on a solid like a carpet, wood, or concrete floor would

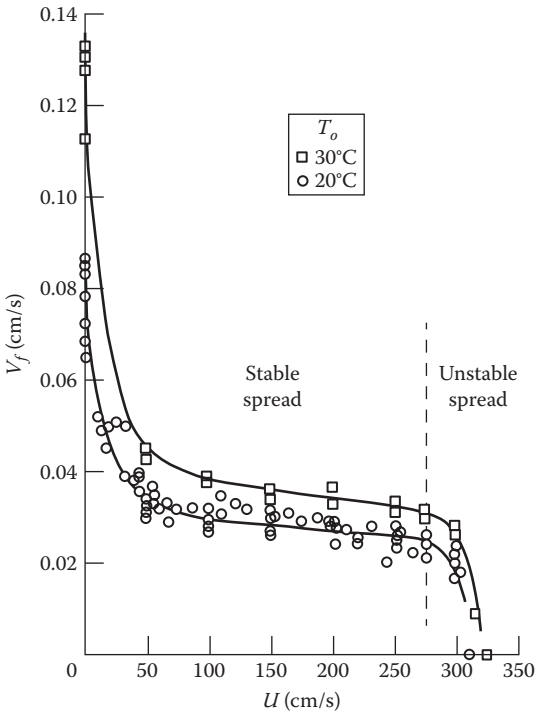

FIGURE 5.12
Flame spread on a kerosene soaked sand bed as a function of opposed air speed. (From Suzuki, T. et al., Flame spread over soaked sand in an opposed air stream, in: *Proceedings of the Second International Symposium on Fire Safety Science*, 1989, pp. 199–208.)

not possess the same flow effects. The spread will be slower than a pool of liquid. The liquid and porous solid would act like a composite, and the heat loss into the solid would mitigate the spread. Figure 5.12 shows data for kerosene soaked into a bed of sand from Hirano and coworkers.[10] In the figure, the effect of opposed-flow velocity is shown on the flame speed. In still air, the radiation from the vertical flame leads to the highest spread rate in these experiments. As the air speed increases, the flame is blown over into a thin boundary layer flame that heats the fuel ahead by convection mostly. Over an air speed of about 300 m/s, the flame is blown off.

5.7 Spread through a Dwelling

Distinct spread in a particular medium has been discussed. It is far more complex to determine the fire spread rate through a series of rooms. However, experiments were done some time ago, and the overall fire

growth rate was measured in terms of the volume of the fire and the consistency and nature of the fuel in dwellings. The results are quite simplistic, yet their predictability from basic principles is explainable. Apply Equation 5.1 to this case. The rate of the volumetric fire growth can be represented as *VA* (speed times area, and note the units: $m/s \times m^2$ is m^3/s). The heat transfer put out by the fire would increase with the volume of the fire, so heat transfer could be taken as proportional to the fire volume as a first approximation. This indicates that the rate of growth for the fire volume is proportional to the volume of the fire itself. The constant of proportionality depends on the fuel and its configuration. We would expect the density, specific heat, and ignition temperature of the fuel in the rooms to affect this constant. This simple result yields that, for a given consistency of fuel in a series of rooms, the fire volume will double in a fixed time. This fire doubling time for normal dwellings might range from 2 to 10 minutes. Figure 5.13 shows data from a dwelling with similarly distributed fuel among its rooms.[11] It has a fire volume doubling time of 7.5 minutes. When the ratio is 2, the time is 7.5 minutes, and at 4 it is 15 minutes, and so on. So, this complex fire growth through a building can be classified into a quantitative format.

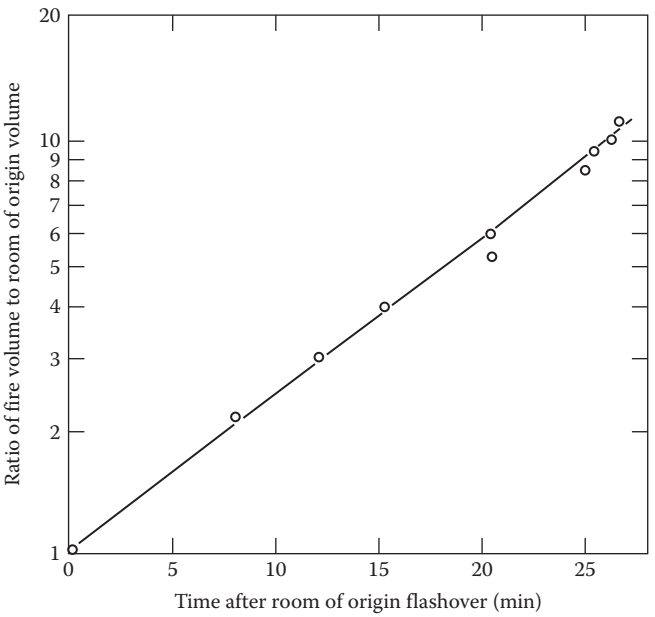

FIGURE 5.13
Fire growth in a dwelling. (From Labes, W.G., *Fire Technol.*, 2(4), 287, May 1966.)

5.8 Typical Fire Spread Rates

As we have seen, flame spread is a complicated phenomenon of fire growth that does not easily lend itself to quantitative analysis. Formulas do exist, and they fit a simple framework (e.g., Equation 5.2). But they are usually lacking in information for the specific heat flux and fuel properties. However, with some estimations, data and formulas can be used to arrive at representative results.

To put fire spread rates in perspective, Table 5.2 lists typical values that may be useful in characterizing different spread phenomena. Even without the application of formulas, the table data can usefully characterize fire spread phenomena. Smoldering spread is likely below 0.01 cm/s, opposed-flow flame spread normally is of the order of magnitude 0.1 cm/s, and forest spread through fine needles, liquid spread and wind-aided spread could range from roughly 1 to 100 cm/s at most. Anything greater is gas-phase premixed flame propagation.

5.9 Standard Test Methods

A number of flame spread–based test methods exist for materials, some of which form the basis for fire safety regulations in the United States. Most of these tests produce relative indexes for assessing spread and do not support basic data for the computation of flame spread. Some can even be misleading because the test performance may not reflect realistic fire scenarios. Other tests have played a traditional role in regulating fire safety and have been supported on an empirical bed of data (see Table 5.3). The **Steiner tunnel test (ASTM E-84)** is a wind-aided flame spread test with the material on the ceiling of a duct. It gives a flame spread rating that is normalized at a rating of 100 for the rate associated with burning red oak. Although **ASTM E-162**

TABLE 5.2

Typical Flame Spread Rates

Spread	Rate (cm/s)
Smoldering	0.001–0.01
Lateral or downward spread on thick solids	0.1–1
Wind-driven spread through forest debris or brush	1–30
Upward spread on thick solids	1–100
Horizontal spread on liquids	1–100
Premixed flames (laminar)	10–100
Premixed flames (detonations)	$\approx 10^5$

TABLE 5.3

Empirical Standard Flame Spread Tests

ASTM Designation: E-84
Standard test method for surface burning characteristics of building materials
ASTM Designation: E-162
Standard test method for surface flammability of materials using a radiant heat energy source
ASTM Designation: E-648
Standard test method for critical radiant flux of floor-covering systems using a radiant heat energy source
ASTM Designation: E-1321
Standard test method for determining material ignition and flame spread properties

is a downward flame spread test, its measurements are processed to give similar index results to ASTM E-84. **ASTM E-648** is one of the few tests that actually give results in engineering terms. It gives the minimum heat flux required for horizontal flame spread on a floor material. In contrast, ASTM E-1321 is not used for regulatory purposes but generates engineering data for flame spread computations. Such data have been listed in Table 5.1. Suffice it to say that no standard test has been invented that directly gives a full set of engineering data needed to predict flame spread. This deficiency is a serious problem in assessing the fire growth hazard of new materials and their applications. Also, the reliance on test results without a consideration of the fire scenario is problematic.

5.10 Case Study: Fire Spread in a School Gymnasium

Several years ago, I investigated a fire in a high school gymnasium (Figure 5.14). I usually take my job as trying to explain what happened. But no one can exactly know how any fire progressed. In this case, the issue was what product was significant in spreading the fire beyond the upper gym. The fire was clearly seen on a pile of head-high mats against a wall. An attempt was made to suppress it with available portable fire extinguishers. These untrained observers failed to suppress the mat fire and vacated the gym while the fire was still on the mats. They proceeded by moving away down the corridor. As they progressed, they looked back and saw, through the corridor wall glazing, that the fire had just started to bridge the upper corner of the wood partition wall about 20 ft above the upper gym floor. This occurred in less than a minute.

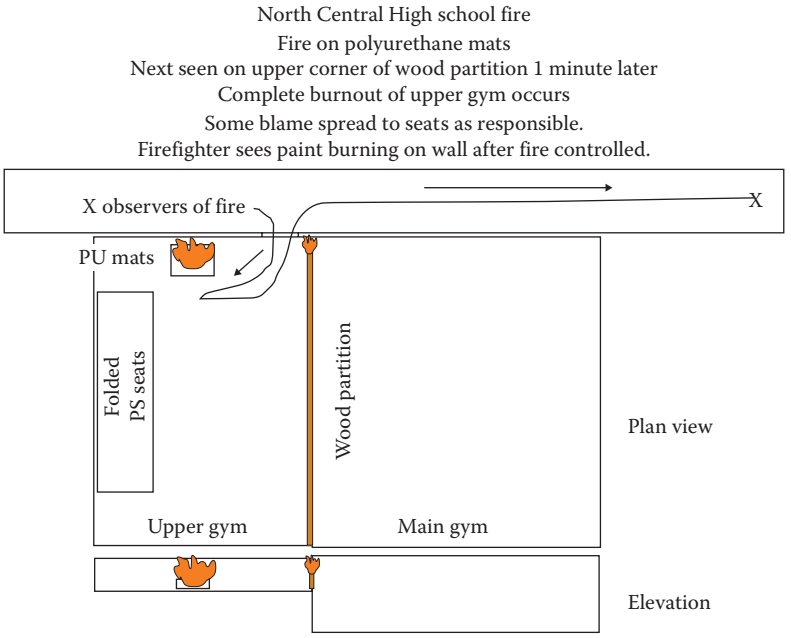
North Central High school fire
Fire on polyurethane mats
Next seen on upper corner of wood partition 1 minute later
Complete burnout of upper gym occurs
Some blame spread to seats as responsible.
Firefighter sees paint burning on wall after fire controlled.
X observers of fire
X
PU mats
Folded PS seats
Wood partition
Plan view
Upper gym
Main gym
Elevation

FIGURE 5.14
Gymnasium fire.

Some investigators argued that the fire progressed from the mats, along possibly some floor mats, to the bleacher seats made of polystyrene. They suggested that flames from the bleachers attacked the wood partition wall. If we consider about 10 m to the bleachers, a floor fire would propagate at about 0.1 cm/s, and it can be computed then to take more than 2 hours to move that distance. Even if one might say the polyurethane mats might melt to form a liquid pool, bumping up the speed to 1 cm/s, still this gives an inconsistent time (12 minutes) relative to the time taken by the observers. Now the flame height on the pile of mats could barely reach the ceiling. So, how could the fire move from the mats to involve the wood partition at the ceiling level? After reading much material, I came across an observation of a firefighter that was mopping up in the upper gym after the fire had ravished the school. He said some of the paint on the concrete block wall was still burning. Realizing now that the paint, and likely many coats, was on the wall, we now have the possibility of upward fire spread. Considering a propagation rate in this wind-aided direction to the wood partition, we can estimate a speed of at least 1 to say 10 cm/s for a travel distance of about 10 m. We now get about 100–1000 seconds

(or about 1–10 minutes) to reach the partition. This scenario is much more plausible, especially recognizing that such a wind-aided fire will accelerate. Hence, this scenario is likely what happened, and it is consistent with the time period taken by the witnesses. We have not precisely predicted this fire growth, but we have used the science of fire to make a rational analysis and found the most consistent scenario.

In general, paint on inert concrete can ignite and burn. In NYC, paint on concrete block walls in stairwells of public housing was found to be responsible for several fires that propagated up many floors. The city sought a remedy to either cover or remove the paint. These two painted wall examples indicate the hazard of upward flame spread. Of course in both cases, a significant fire had to get it going.

5.11 Summary

Fire spread can occur through gaseous fuel at incipient speeds of 10–100 cm/s reaching detonations in confined regions of 10^5 cm/s. On the other hand, surface flame spread can range from 1 to 100 cm/s on liquids and solids, especially if it is wind driven. Downward or lateral spread can have much lower speeds, and smoldering almost stands still at 0.001–0.01 cm/s. All of these speeds contribute to the fire growth and the extent of the burning region. The extent of the burning region is directly related to hazard and damage due to fire.

Theories have been described to illustrate the factors important in fire spread and to provide a framework for computations. Fire spread depends on many factors: the fuel, its orientation, the wind, the direction of spread, and heat transfer. Fire spread velocity can be described as the ratio of the flame heated distance to ignition time. The heated distance depends on the *reach* of the fire's direct heat flux. It has been shown how such a simple theory can be applied to the many situations encountered in fire spread.

This chapter has dealt with the nature of flame spread and how to estimate its speed. But for most common materials, flame spread is not always possible under normal atmospheric conditions. In opposed-flow spread, the leading edge flame is a premixed flame. If its heat losses are too great to sustain a flame temperature in the range of 1300°C, the flame will extinguish. If the opposed wind speed is too great, the fuel will not have enough time to completely react, and the flame will die—blown out. Under wind-aided flame spread, if the flame does not extend sufficiently in the forward direction to heat the new material to its ignition temperature, the flame will not advance. The issue of extinction is complex, and simple formulas do

not generally apply. But one must always be aware that flame spread is not automatic. Yet if it occurs, the formulas presented here can give reasonable estimations and explanations of flame spread behavior.

Review Questions

1. Data for a cardboard match are as follows: Treat the cardboard as thick.
   k = 0.20 W/m-K
   ρ = 550 kg/m^3
   c = 2.5 J/g-°C
   ϕ = 12 kW^2/m^3
   T_{ig} = 350°C
   a. Compute the TRP of the cardboard.
      Assume the flame imparts a heat flux of 50 kW/m^2. At normal room temperature, T_∞ = 20°C, compute the flame spread speed in b and c.
   b. For downward spread, the heating distance (δ_f) is 1.5 mm.
   c. For upward spread when the flame extends from the pyrolysis front by 2 cm.
2. A rigid foam plastic wall lining is ignited. The flame heat flux is 25 kW/m^2, and after several seconds, it extends 1.5 m from the ignition region. Compute the upward spread speed using data in Table 5.1.
3. Dry grassland has a bulk density of 25 kg/m^3. On flat ground with a wind speed of 20 mph, estimate the possible flame speed through the grass. What if there was no wind?
4. List all the possible factors that could control flame spread.
5. Could flame spread on a steel clad foam plastic occur if there are joint seams in the steel?

True or False

1. Thickness is not a factor in flame spread.
2. As materials are heated by hot smoke in a fire, they will spread faster than at normal temperatures.
3. Flame spread factors on liquid fuels are the same as that on horizontal solids.
4. The bulk density or porosity of forest brush is an important variable in flame spread.
5. Winds do not change the spread rate but can blow out the fire.

Activities

1. Tape the edges of strips of paper so as to suspend them from a wire clothes hanger. The tape is used for mounting and holding the paper in place. Ignite the vertical strip to observe upward and downward spread. See if you can observe the leading edge premixed flame in the downward propagation. Try to clock the time for the pyrolysis front to spread over the strip. Moisten the paper with alcohol (ethyl or methyl) and repeat the tests. Explain your results. *Caution*: Such an experiment needs to be done in a safe place, not in your home.
2. Place two 2 × 4's about 1 foot high together. Find the gap thickness that will allow flame to spread up or down the gap by using a match flame size ignitor. Explain your results.
3. Obtain a shallow metal or glass tray about 6–10 in. long and 1 in. wide. Separately pour kerosene, then methyl or ethyl alcohol into the tray about 1/4 in. in depth. Ignite one end and record the spread time. Do not let the alcohol sit long. Explain the results. Again be cautious in doing this. It should be done in an appropriate setting with safety precautions taken.

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6

Burning Rate

Learning Objectives

Upon completion of this chapter, you should be able to accomplish the following:

- Describe the factors influencing energy release rate.
- Execute formulas to predict burning rate and energy release rate.
- Define heat of gasification and heat of combustion.
- Select or construct energy release rate signatures of real items.

6.1 Introduction

The fire triangle (fuel, oxygen, and energy) helps to explain the nature of fire, but ignition, flame spread, and burning rate, as illustrated in Figure 6.1, comprise the elements of fire growth. You need this trifecta to achieve growth. Ignition tells us when fire growth begins, flame spread theory allows us to define the extent of the fire's boundaries, and burning rate gives us the consumption of fuel within those boundaries. In this chapter, we describe how objects burn, gasifying their liquid or solid fuel from the heat of their own flame. A burning rate theory is presented, but real objects demand real data. We demonstrate how to use these data.

6.2 Definitions and Theory

Burning rate is defined as the mass of solid or liquid fuel consumed per unit time. By consumed, we mean it chemically reacts with oxygen. In large structural fires, fuel may vaporize due to heating, but not immediately burn due

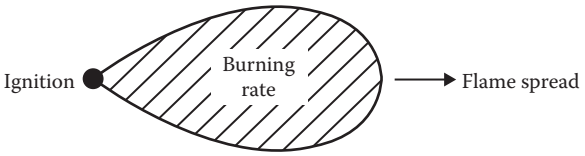

FIGURE 6.1
The trifecta of fire growth.

to limited oxygen. Burning is combustion; *fuel supply* is that flow of burnable gases that potentially can make a flame. Therefore, one must distinguish between the *mass loss rate of fuel* in fire as fuel supplied and as the mass burned (fuel reacted with oxygen). In this chapter, we are considering the burning of single objects primarily in air. Here, these two distinct quantities—mass loss rate or supply rate and burning rate—are considered synonymous. We consider all of the supplied fuel to be burned here. So, if we burn a pan of alcohol on a scale (Figure 6.2), the heat from the flame will cause the liquid to evaporate and its mass loss can be recorded over time. The mass lost divided by the time to lose this mass is the mass loss rate, $\dot{m}$, usually conveniently expressed in grams per second (g/s). Here it is synonymous with burning rate as it is very likely that all of the alcohol evaporated will be consumed in the flame, leaving products of combustion obviously behind. Some of the products of combustion can still be compounds of that might be capable of still reacting. If the products do not go to their normal stable states (e.g., water vapor and carbon dioxide for hydrocarbons), the chemical reaction with oxygen is termed "incomplete."

If we were to simply let the alcohol evaporate without ignition, the mass loss rate would not be synonymous with burning. However, in this chapter, for a material or object with free exchange of normal air, once ignited, the fuel supply rate and burning rate will be considered to be one and the same.

In order to ignite the alcohol in the pan in Figure 6.2, it must at least be at its flashpoint temperature. Alcohols typically have their flashpoints less than normal air temperature, so a small flame near its surface will cause ignition. Once a diffusion flame forms over its surface, the surface temperature increases to nearly its boiling point. The boiling point is the maximum temperature a pure liquid can reach when heated in normal atmospheric conditions. If we boil water at sea level (1 bar), it would reach 100°C, but on Mt. Everest (0.260 bar), it boils at 69°C. So as a liquid fuel is heated, its temperature rises, and its evaporation rate increases. But the temperature at the surface of a pure liquid cannot exceed its boiling point. Hence, the alcohol will start to burn at its flashpoint as a short duration premixed flame, then as the diffusion flame forms (fire point) and gets bigger, the liquid temperature will reach its boiling point and stay there. During this increase, the rate of evaporation or the burning rate also increases accordingly. This leads to an initial burning rate once ignited and then an increase

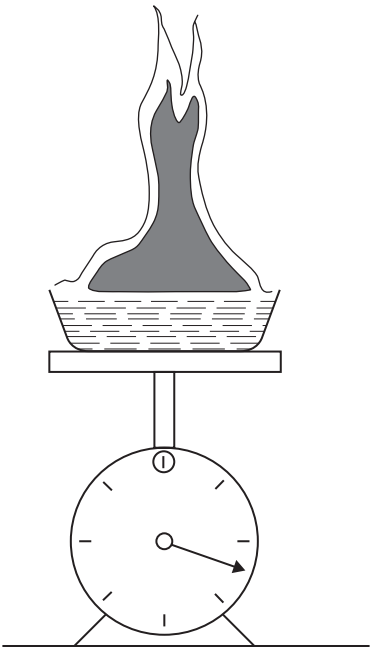

FIGURE 6.2
Measuring the burning rate.

until the rate becomes relatively steady. This changing or unsteady burning is typical of the way fuels burn. They will start low, then increase, and try to reach a steady state. But complex fuels, like wood that char, will first increase then decrease as the insulating char layer prevents the heat to get to the virgin wood.

6.2.1 Burning Mass Flux

In general, the rate of burning depends on the fuel properties, its orientation or configuration, and the area involved. Wood logs burn well together, but not alone. A surface may burn easily on its underside, but not its topside. The area of burning is controlled by the ignition and flame spread processes. The rate of burning over that area may not be steady and may not be uniform. The character of uniformity can be expressed by the intensity of burning over the surface. This quantity is expressed as burning rate per unit area or *mass burning flux*, $\dot{m}''$. It describes how each point on the surface burns. If we divide the fuel supply area into small surface regions, associating each surface with an $\dot{m}''$, then the sum of $\dot{m}''$ times each corresponding surface area gives us the total rate of burning. In the calculus, this would be refined as an integration of the mass flux over its area.

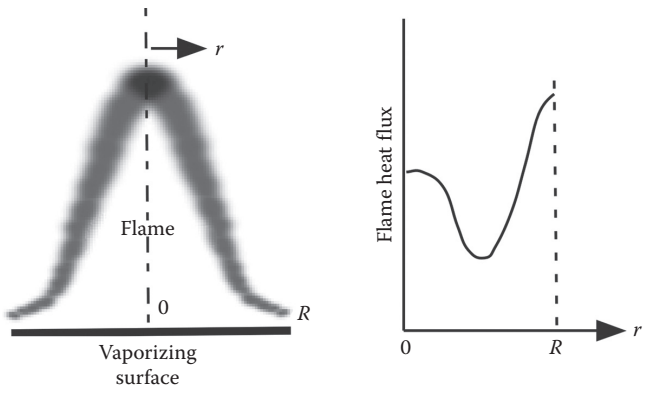

FIGURE 6.3
Illustration of nonuniform burning.

This intensity of burning is analogous to the characterization of a sprinkler spray hitting the floor below. Putting buckets on the floor to catch the individual water amounts can be used to find the local intensity of the spray in terms of typically gpm/ft^2. In sprinkler nomenclature, this intensity is commonly called the "water flux density" or just "water density."

Figure 6.3 shows an illustration of how the local burning flux can vary. It depicts a small laminar flame, like a candle size. The flame at the edges will be near the surface and have a high heat flux. As the flame is farthest away from the surface at its center, the heat flux will drop. But in the center region, the flame could be thicker and may possess some radiation as well as convection. This added radiation could make the heat flux increase. In this way, the heat flux can have this bimodal distribution about the center as shown in Figure 6.3. The heat flux distribution is directly responsible for the evaporation rate or burning rate of the fuel at each point. Therefore, each point on the surface will have a corresponding mass flux and will vary in accordance with this surface heat flux.

6.2.2 Heat of Gasification, *L* (kJ/g)

The *heat of gasification* can be regarded as a property of a liquid or solid fuel. It is the energy needed to make the solid or liquid produce a vapor and is defined on a unit mass basis of the vapor, commonly given in kJ/g. It is an exact thermodynamic property for liquid fuels and can be expressed with great accuracy. For a liquid, it represents the sum of energy needed to evaporate the liquid at the surface, plus the energy needed to bring the liquid from its original temperature to its boiling point. For a pure liquid, the vapor produced will be the same chemical as the liquid. For a solid, the solid might melt then gasify, or simply *pyrolyze* (thermal decomposition) to a vapor. Both the melt and the vapor are rarely the same compound as

the solid. Indeed, for charring solids, the original solid will transform in thermal decomposition to both char and vapor, simultaneously. The heat of gasification is not an exact property for the solid because of its decomposition to new compounds.

The utility of the heat of gasification is that it can be used to predict the burning rate. Although imprecise and approximate for solids, its measurement process shows that it can be determined with reasonable consistency. Its subsequent use then depends on this measurement process. Typically that process adds a known amount of energy to the solid or liquid by heat transfer. The solid or liquid is placed on a scale, and its mass loss due to gasification is recorded. Repeating this measurement with varying amounts of energy or heat transfer, and averaging the results over time, leads to a fairly constant value for the energy added per mass lost. This output is the heat of gasification. It can depend on how the process is averaged over time. For example, for a charring solid, it might be averaged only over the period of high mass loss rate. Alternatively, it might be averaged over the entire gasification time. Usually the peak burning condition is used for solids. In any case, the heat of gasification is a precise property for a liquid, but an approximate property for a solid.

6.2.3 Approximate Formula for Steady Burning

A general predictive formula for the mass burning rate per unit area, or *mass burning flux*, is given in terms of the heat of gasification as

$$\dot{m}'' = \frac{\dot{q}''}{L} \tag{6.1}$$

where $\dot{q}''$ is the net heat flux to the fuel surface.

This formula applies exactly to the steady burning of a deep liquid pool. It gives the final steady burning flux for the pool. For solids, it gives only an average result over the flaming period. As typical data on L for solids are based on the average peak burning rate, Equation 6.1 attempts to predict the peak burning conditions.

For shallow liquid pools or liquid fuels saturated into solids, the formula overestimates the mass burning flux because of heat lost into the substrate of the liquid. Also, for something like gasoline poured on wood, the gasoline would burn off first. The wood would assume the boiling point of the gasoline fuel components. As the less volatile components of the gasoline begin to vaporize, the wood temperature would rise. If sufficient heat transfer remains after the gasoline burns off, the wood might begin to vaporize and continue to burn. A burning liquid fuel with a low boiling point absorbed into the wood is likely to only cool a horizontal piece of wood (except at the edge of the flame where the wood is dry).

6.2.4 Computing the Mass Burning Flux

The heat flux in the equation is the sum of heat from all possible sources. In a fire, the heat comes from the flame and the heated surroundings. Because the surface of the material burning is relatively hot, it will radiate heat to the surroundings. In the formula of Equation 6.1, the net heat flux for a material in a fire is composed of the flame above the surface (the incident flame heat flux, $\dot{q}''_{flame}$) and external radiant heat flux from hot surroundings ($\dot{q}''_{ext}$). In addition, there is a *reradiation* term due to the radiant energy emitted from the surface. The reradiation flux $\dot{q}''_{rr}$ can be estimated as approximately the blackbody radiation from the vaporizing surface. It is always greater than the critical flux for piloted ignition (CHF). In the event that the reradiation flux is not known, one might use CHF as a first low estimate.

The net heat flux for a fire condition is the algebraic sum of the heat flux components at the surface as shown in Figure 6.4. So the *net heat flux* is given as

$$\dot{q}'' = \dot{q}''_{flame} + \dot{q}''_{ext} - \dot{q}''_{rr} \tag{6.2}$$

This formula would apply for a material burning in a fire that is heated by both its flame and radiation from the surroundings. For other scenarios, it would have to be modified. For example, a material burning on its own in normal ambient air would only have the incident flame heat flux and the radiant exchange between the surface and the ambient surroundings. On the other hand, in a test apparatus to measure L, the process might take place in nitrogen with heat transfer from a radiant heater. For this case, there would be no flame heat flux in the formula. The measurement or estimation of these heat fluxes in different scenarios is crucial to using Equation 6.1 to estimate *steady* burning.

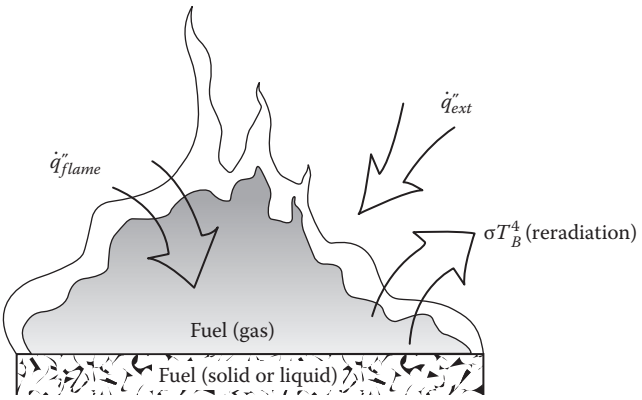

FIGURE 6.4
Heat flux components causing burning on a horizontal surface.

6.2.5 Unsteady Burning

In general, materials will not burn in a steady fashion even under fixed heating conditions. At ignition, a material will have a minimal mass flux. Once the flame occurs, additional heat will be applied, and the burning rate will increase. Equation 6.1 for a deep pool liquid will give the final steady burning rate. Typically it will take some seconds to reach this value. For melting solids, it could take minutes. For charring solids, the process is more complex because of the increasing char layer that builds up. Initially, the charring material will burn like a melting solid and try to achieve a steady value. However, as the char builds up, it forms an increasing insulating layer. The char is porous, as the vaporizing component has been depleted from the original material. Also the char tends to be nearly all carbon and is effectively inert. This inert increasing porous layer allows vapor from the virgin material to easily pass through it but diminishes the heat transfer by conduction from the flame to the virgin material. This reduced heat transfer causes the burning rate to decrease. As the char layer increases, less and less heat can be transferred to the virgin solid material for vaporization. The flame will be sustained until the burning flux gets to a critically low value and extinguishes. The flame elimination is followed by direct oxidation of the char. Smoldering then ensues, and the char slowing burns away. Once the char is depleted, flaming could resume if sufficient heating persists at the surface. Charring materials, such as heavy timber, likely burn in this repeated fashion in building fires.

Figure 6.5 shows how wood behaves in horizontal burning at an external heat flux of 50 kW/m^2. Up to about 350 seconds flaming is sustained, then smoldering ensues. During both periods, the mass loss rates appear almost constant at about 40 g/440 s = 1/11 g/s for flaming and about 5 g/800 s = 1/160 g/s for smoldering. On closer inspection there is a sharp decrease in mass at about

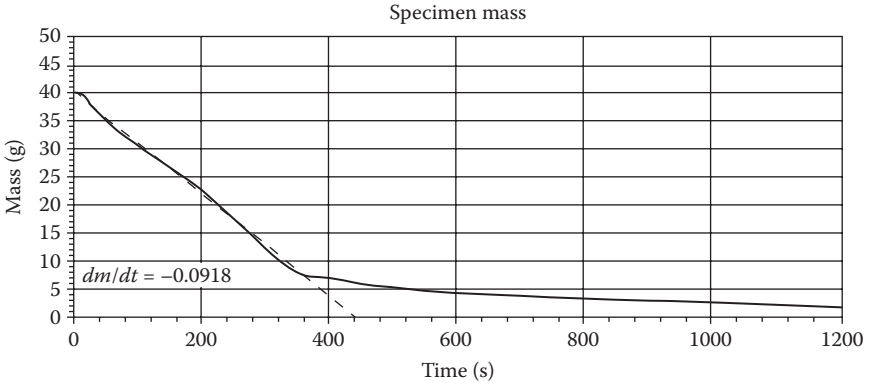

FIGURE 6.5
Burning of wood with an external heat flux of 50 kW/m^2. (From Dillon, S.E. et al., Determination of properties and the prediction of the energy release rate of materials in the ISO 9705 room-corner test, NIST-GCR-98-753, NIST, Gaithersburg, MD, June 1998.)

20 seconds. This is the peak burning rate before the char interferes with the heat transfer into the wood. Later at about 200 seconds, there is a slight increase in the rate of mass loss until about 350 seconds where it slows to smoldering. This slight increase in the mass loss rate is likely due to the noncombustible insulation on the back face of the wood that traps more energy into the virgin wood.

The L value for the wood in this experiment depends on the period of burning over which it is averaged in Equation 6.1. The surface of the burning wood increases in temperature as the char builds up, and therefore, the reradiation heat flux increases. The flame heat flux changes as the mass loss decreases, and the incident radiant heat flux of 50 kW/m^2 remains the same at the surface. However, the heat flux arriving at the virgin wood will decrease. The virgin wood has inherently a reasonably well-defined heat of gasification; however, the heat of gasification derived from such an experiment will use the known heat flux from the radiant source, a measured heat flux from the flame at peak burning conditions and an associated reradiation heat flux. L will likely be computed from the measured mass loss rate of the peak burning condition.

6.2.6 Difficulties in Computing Burning Rates

In the context of the simple formula in Equation 6.1, L is only a very approximate property for char formers. Nevertheless, Equation 6.1 gives us a simple, but proper, quantitative tool for estimating the mass burning flux. Unfortunately, the net heat flux $\dot{q}''$, or more specifically, the flame heat flux, is not readily available from the literature. This is a quantity not easily predicted. While L is a property of the liquid or solid, the net heat flux depends on the flame: its size, orientation, soot concentration, and flow conditions. We must rely on data and insight to achieve practical estimates for it.

Typical mass burning fluxes for materials can range from about 1 to 100 g/m^2-s. Values below 1–2 g/m^2-s usually lead to extinguishment. As shown directly by Equation 6.1, external heating added to the flame heat flux will increase the mass burning flux. Such external heating can arise from a fire in a room resulting in a feedback loop that can accelerate burning. The room gets hot giving more heat flux; more heat flux makes the burning rate increase. This added burning makes the room get hotter. This is the feedback loop that increases the burning mass flux as the room gets hotter. However, the oxygen level in the room can eventually mitigate this process since low oxygen will drop the flame temperature. In general, atmospheric oxygen is directly related to flame temperature. For that reason, burning in elevated oxygen atmospheres will give a higher flame temperature and burning rate than burning in vitiated (depleted oxygen) atmospheres.

Suppressing a fire by cooling with water can lead to extinguishment of the flame as the critical mass flux level is reached. This cooling effect can be taken as an effective heat loss flux due to evaporation and might be included in Equation 6.2. Qualitatively, the effect of suppression by water can be explained, but quantifying this effect has not been generally developed.

Accordingly, Equation 6.1 can help explain a range of burning rate effects. It can explain the increase in burning in a room, it can explain a decrease in burning if the ambient oxygen drops, and it can explain the suppression by water to a critical value for extinction. However, methods to predict the various heat fluxes needed in Equation 6.1 are nonexistent or empirical at best.

6.2.7 Material Property Values for the Heat of Gasification

Typical values of heats of gasification are listed in Table 6.1. In addition, the reradiation heat is listed, if known. These data have been assembled from various sources and are only generically listed. A manufactured material would only be representative of its type. For pure liquids, the heat of vaporization and boiling temperatures are distinct and precise. For charring materials and commercial products, these quantities are approximate. Chemical additives and the physical form of the material (granular, foam, solid) can affect the value of L for solid fuels. Indeed, a chemical retardant could increase L for the solid fuel, making it more difficult to vaporize. As was stated, values of L for pure liquid fuels are precise properties, while for a material such as wood, it is approximate because it includes the effect of char and changing conditions over time. Moreover, the use of such approximate L values from Table 6.1 attempts to give an estimate of the peak burning conditions. For steady or near peak burning condition, the L includes the energy needed to vaporize, plus the energy needed to bring the material to its vaporization temperature. A pot of water in full boil will be at 100°C throughout, not just at the surface. So for pure liquids, burning at a full boil, L would not include the energy needed to bring the rest of the liquid to its boiling point; it would already be at that value. So under full boil conditions, L for a liquid in Table 6.1 will be lower than that given.

As the degradation process becomes more complex, as for char formers, L is an approximate representation of the process. For solid fuels, approximate values of L have been deduced by special heating experiments based on using Equation 6.1. In general, it can be seen from Table 6.1 that values of L tend to increase as we move from liquids (<1 kJ/g), to melting plastics (1–3 kJ/g), and then to char formers (3 kJ/g and higher). This is generally true. Liquids are easiest to vaporize and char formers require a lot more energy to get the virgin material to vaporize.

6.3 Estimating Burning Mass Flux

Although Equation 6.1 is a useful quantitative tool in explaining burning rate, it has limited practical use. The principal problem is how to specify the flame heat flux. This quantity can depend on the fuel, its orientation, its configuration, and its environment.

TABLE 6.1

Burning Properties of Materials

Materials	Reradiation Heat Flux, $\dot{q}''_{rr}$ (kW/m^2)	Heat of Gasification, L (kJ/g)
Liquids		
Gasoline	~0.5	~0.33
Hexane	0.88	0.45
Heptane	1.07	0.50
Kerosene	~3.7	~0.67
Ethanol	0.86	1.00
Methanol	0.74	0.74
Ordinary polymers		
ABS, acrylonitrile–butadiene–styrene	10	1.4, 3.2
PE, polyethylene	15	1.9
HDPE, high-density polyethylene	15	2.0, 2.2
PP, polypropylene	15	2.0
PVC, polyvinylchloride	15	1.5, 2.5
PS, polystyrene foams	10–13	1.3–1.9
Nylon 6,6, polyamide	15	1.5, 2.4
PMMA, polymethylmethacrylate	11	1.6, 2.3
POM, polyoxymethylene	13	2.0, 2.4
PU, polyurethane rigid foams	14–22	1.2–5.3
PIU, polyisocyanurate foams	13–37	1.2–6.4
PE foams	12	1.4–1.7
High-temperature polymers		
Phenolic foam	20	1.6
Phenolic/glass fibers	20	7.3
PC, polycarbonate	11	2.1, 4.8
Phenolic–aromatic polyamide	15	7.8
Halogenated polymers		
FEP, perfluoroethylene propylene	38	2.4
ETFE, ethylene tetrafluoroethylene	48	0.8–1.8
CPVC, chlorinated PVC (25%–48% Cl)	10–12	2.1–3.1
Wood and wood products[a]		
Redwood	—	4.6, 9.4[b]
Red oak	—	7.9, 9.4[b]
Douglas fir	—	6.8, 12.5[b]
Maple	—	4.7, 6.3[b]
Plywood	—	7.3
Plywood, FR (fire retarded)	—	9.3
Chipboard, FR	—	10.0

(*Continued*)

TABLE 6.1 (*Continued*)

Burning Properties of Materials

Materials	Reradiation Heat Flux, $\dot{q}''_{rr}$ (kW/m²)	Heat of Gasification, L (kJ/g)
Composites[a]		
Paper of gypsum board	—	4.8
Wallpaper on rigid PU	—	5.5

Sources: Dillon, S.E. et al., Determination of properties and the prediction of the energy release rate of materials in the ISO 9705 room-corner test, NIST-GCR-98-753, NIST, Gaithersburg, MD, June 1998; Tewarson, A., Flammability of polymers, Chap. 11, in: Andrady, A.L., ed., *Plastics and the Environment*, John Wiley & Sons, Inc., Hoboken, NJ, 2003; Panagiotou, J. and Quintiere, J. G., Generalizing the flammability of materials, in: *Proceedings of the 10th International Conference on Interflam 2004,* Interscience Communication, London, U.K., 2004, pp. 895–906; Spearpoint, M.J., Predicting the ignition and burning rate of wood in the Cone Calorimeter using an integral method, Masters thesis, Department of Fire Protection Engineering, University of Maryland, College Park, MD, 1999.

[a] Based on peak average burning.

[b] Heating parallel, perpendicular to wood grain.

6.3.1 Example for a Burning Wall

For burning walls, not exceeding about 2 m tall, the wall flame heat flux to the wall appears to have an approximate constant value of 25 ± 5 kW/m² independent of the material. This gives us a strategy for estimating the burning rate of such a wall fire.

Example 6.1

Consider a burning wall of nylon 6/6 having a vaporization temperature of 380°C. Estimate its burning mass flux.

Assume for the flame an incident heat flux = 30 kW/m² as a typical wall flame.

Compute the reradiation surface heat flux from blackbody theory of radiation for a surface temperature of 380°C.

$$\sigma T^4 = 5.67 \times 10^{-11}\ \text{kW/m}^2\text{-K}^4\ (380 + 273)^4 = 10.3\ \text{kW/m}^2$$

This value of 10.3 kW/m² for the reradiation flux of nylon 6/6 computed here is in contrast to 15 kW/m² given in Table 6.1. The difference is in the vaporization temperature of that particular nylon or in the measurement accuracy of vaporization temperature of the nylon.

Since this reradiation heat flux is lost from the surface, the net heat flux is computed as

$$\dot{q}'' = 30 - 10.3 = 19.7\ \text{kW/m}^2$$

From Table 6.1, the heat of gasification, L, is taken as 2.4 kJ/g. The burning mass flux is now computed as

$$\dot{m}'' = \frac{\dot{q}''}{L} = \frac{19.7}{2.4} = 8.2 \text{ g/m}^2\text{-s}$$

If we had selected 1.5 for the heat of gasification from Table 6.1, the result would be higher.

This example illustrates how, for this wall configuration, we can develop an estimate for the burning mass flux. It also illustrates the variations in the estimation process due to the uncertainty of generic properties. An accurate value could only be obtained from precise values for the particular nylon on the wall. The fact that the computed value is above the critical value for extinction of about 2 g/m^2-s says that the nylon wall will sustain burning. As nylon melts, no consideration of melting is included in this estimate. The nylon could drip, the wall could fall onto the floor, or simply distort in other ways due to melting. This aspect is not included in the formula. It assumes the nylon stays in place on the wall with the flame heat flux specified.

6.3.2 Pool Fires

For other configurations other than a vertical wall, we cannot easily settle on estimates of $\dot{q}''$ without data from specific experimental measurements. Consider the horizontal burning configuration of Figure 6.4. For liquid fuels, a variety of experiments have been conducted. From these experiments, it was found that the diameter of the liquid pool has a significant effect on the heat flux, and therefore the burning flux. A typical burning mass flux curve is shown in Figure 6.6 for methanol. For very small diameters, $d < 5$ cm, the flame is laminar in character, possessing a very thin flame of nearly 2000°C. As the diameter increases in this range, the flame sheet moves farther from the surface, reducing the heat flux and consequently the mass flux as shown. For the range of 5–20 cm diameter, the flame is more turbulent with a lower heat transfer coefficient and with the average turbulent flame temperature becoming approximately 800°C–1000°C. As we saw in Chapter 3, the convective heat transfer coefficient is roughly 5–10 W/m^2-°C in this turbulent region and invariant with diameter. With temperature differences of up to 1000°C between the flame and the methanol, the convective heat flux from the flame would be about 10 kW/m^2 at most. So, for this turbulent diameter range, the burning mass flux is nearly constant. It can be estimated using the data in Table 6.1 as

$$\dot{m}'' = \frac{10 \text{ kW/m}^2 - 0.74}{1.23 \text{ kJ/g}} = 7.5 \text{ g/m}^2\text{-s}$$

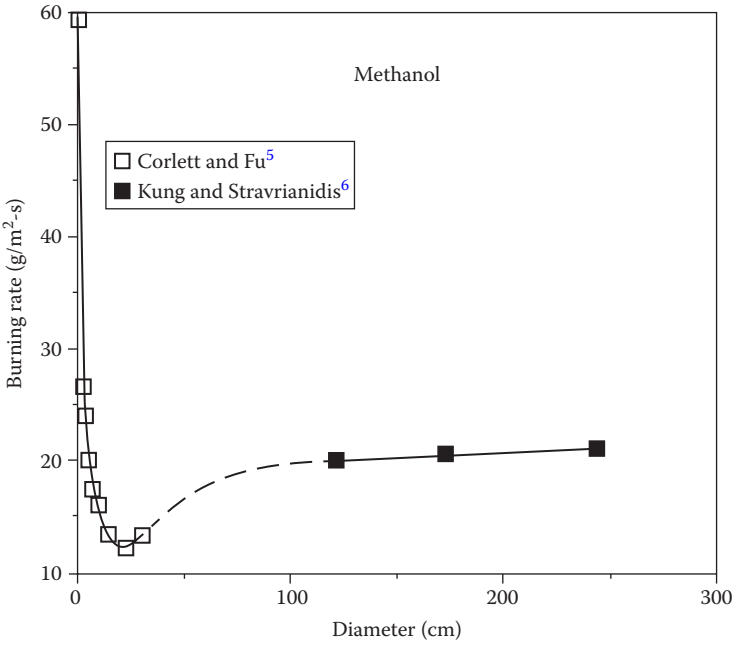

FIGURE 6.6
Burning mass flux for methanol pool fires as a function of diameter. (From Corlett, R.C. and Fu, T.M., *Pyrodynamics,* 4, 253, 1966; Kung, H.C. and Stravrianidis, P., Buoyant plumes of large-scale pool fires, in: *Nineteenth Symposium* (*International*) *on Combustion,* The Combustion Institute, Pittsburgh, PA, 1982, pp. 905–912.)

This computed value is lower than the experimental value in Figure 6.6. (At about a diameter of 20 cm, the burning flux is about 12 g/m²-s.) It shows the accuracy of trying to predict the flame heat flux. Perhaps adding some radiation heat flux from the flame might make the estimate better.

As the diameter further increases, the size and thickness of the turbulent flame increases, providing an increasing source of additional radiant heat flux from the thick flame. However, as we saw in Chapter 3, the flame radiation reaches a maximum value when the flame emissivity becomes equal to 1. As a result, the burning mass flux attains a maximum value when the flame emits at this maximum. The occurrence of this maximum value depends on the sooting tendency of the fuel but generally occurs for a fire diameter of about 1–2 m. A similar result is shown in Figure 6.7 for gasoline pool fires with diameter values greater than 20 cm. The maximum value is seen to reach 55 g/m²-s. All fuels capable of burning in a horizontal pool configuration will attain this type of maximum burning flux. As it occurs around diameters of 1 m or above, it can provide a very good upper limit estimate in computing burning rates in fire for fuels over or near this size.

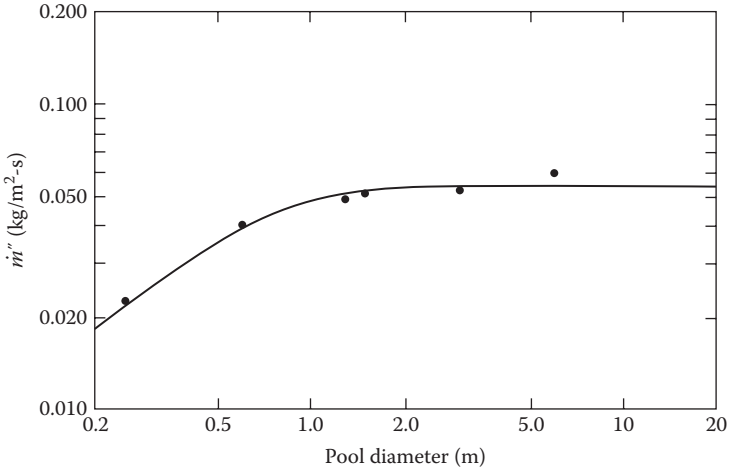

FIGURE 6.7
Mass burning flux for gasoline pools. (From Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.)

6.3.3 Maximum Burning Rates

These maximum pool fire burning mass flux values have been experimentally determined for other liquid fuels, as well as for solid fuel materials, and even arrays of objects. They have been tabulated from various sources in Table 6.2. Although these values must be taken as very rough estimates for the solid fuels, they do offer a framework for computing worst-case burning conditions. Most of the materials in Table 6.2 burn in pool-like configuration with a circular area surface. The last two items—cartons and cribs (array of wood sticks)—should be regarded as low piles with the burning area primarily their top surface. For some of the materials, the flame heat flux has been roughly estimated from using the information in Table 6.1 and Equation 6.1. The maximum burning flux is highest for the liquefied gases, drops off to the liquid fuels, melting solids, and finally, the charring materials have the lowest. The incident flame heat fluxes might be surprising for these big fires. The flames are very turbulent and tall compared to their diameters. This will encourage high radiation from the flames, but the large body of raw fuel near the pool surface and the possibility of soot there as well can block the radiation like a cloud of smoke. So the process of flame heating is very complex. The flame heat fluxes have been estimated in Table 6.2 by Equation 6.1 and data from Table 6.1. These incident flame heat fluxes range from about 20–80 kW/m^2. The order of magnitude is likely correct, but the individual accuracies cannot be assessed. Some of the variation is likely due to the absorption of the flame radiation by the fuel vapor over the surface of the pool.

TABLE 6.2

Maximum Burning Flux Values and Associated Flame Heat Flux Levels

Fuel	Mass Flux, $\dot{m}''$ (g/m²-s)	Estimated Flame Heat Flux (kW/m²)
Liquified propane	100–130	—
Liquified natural gas	80–100	—
Benzene	90	—
Butane	80	—
Hexane	70–80	35
Xylene	70	—
JP-4	50–70	—
Heptane	65–75	36
Gasoline	50–60	19
Acetone	40	—
Methanol	22	28
Polystyrene (granular)	38	70
Polymethyl methacrylate (granular)	28	78
Polyethylene (granular)	26	80
Polypropylene (granular)	24	67
Rigid polyurethane foam	22–25	—
Flexible polyurethane foam	21–27	64
Polyvinyl chloride (granular)	16	37
Corrugated paper cartons	14	38
Wood crib	11	66

Source: Tewarson, A., Generation of heat and chemical compounds in fires, Chap. 3–4, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

The high surface heat flux for the wood crib is an artifact of the stick array. There is a relative high vaporization rate within the pile due to radiation exchange from the sticks, and this gives a relatively high mass flux at the top plane surface and associated heat flux. It is very likely that a 1 m diameter single flat piece of wood in horizontal burning would barely sustain burning if at all. An empirical, but accurate formula to estimate the average burning rate of cylindrical or square sticks of wood depends inversely on the thickness dimension, d (cm), as

$$\dot{m}'' = \frac{0.9 \pm 0.1}{d^{1/2}} \text{ mg/cm}^2\text{-s}$$

For example, the average burning rate of thin match flame from a stick diameter of 2 mm would be $0.9/(0.2)^{1/2} = 2.01$ or 20.1 g/m²-s. Thin objects can easily store energy and burn at higher levels than thick objects. Note this thin matchstick flame can burn at a higher mass flux than the wood crib array in Table 6.2.

6.4 Energy Release Rate, $\dot{Q}$

Perhaps the most important quantity related to fire is the *energy release rate*, or the *firepower* measured in kilowatts, kW, and denoted here by the symbol, $\dot{Q}$. In much of the literature in fire, this has been called "heat release rate," denoted by HRR. It, more than any other factor, represents the size of the fire and its potential for damage. We shall see that it is directly related to flame height, and from Chapter 3, we saw that it is directly related to the radiant heat flux surrounding the fire. The entire potential for fire growth and flashover in a room can be related to $\dot{Q}$.

So HRR in kilowatts is the power of the fire. It is a key number in assessing the "size" of the fire. It is synonymous to the power of a light bulb, your furnace, and even your car (as 1 kW = 1.34 hp). Most average persons do not consider kilowatt as a measure of fire. You should.

Once I was interviewed on national early morning television about a notable fire that had just occurred. I was a novice and seduced by the reporters into speaking. They promised I would not be asked specific questions about the fire, only about the investigative process. Well, such an agreement is void as soon as you as go on the air. After many fire questions that I fielded and dodged, since we had not had any time to really bear into the investigation, I was asked, "Just what do you mean by a large ignition source?" When I said about "200–300 kW," the questions took another path. The response indicated the interviewer did not know how to digest the size of the fire in kilowatts. This is the power of knowing what kilowatts mean in fire.

6.4.1 Heat of Combustion, ΔH_c

The energy release rate is found through knowledge of the burning mass flux. This burning flux times the area over which it acts give us the total burning rate (g/s). The heat of combustion is a property of the fuel that tells us how many kilojoules (kJ) of energy we get for each gram (g) of the fuel gases burned. Consequently, we can write the formula

$$\dot{Q} = \dot{m}'' A \Delta H_c \tag{6.3}$$

where

A is the area involved in vaporization
ΔH_c is the effective *heat of combustion*

The term "effective" heat of combustion is used as opposed to the theoretical or complete heat of combustion. The former applies during the flaming portion of the fire, while the latter assumes all of the fuel burns to chemical

species that can no longer still burn. This is "complete" combustion. The heat of combustion represents the *chemical energy released per unit mass of vaporized fuel that is reacted*. It is possible to measure the theoretical complete value for a solid such as wood in a device called an "oxygen bomb." In this device, all of the combustible content of the wood would be reacted and the resultant energy and mass consumed would be measured. Only inorganic ash would remain. Typically this heat of combustion for a wood (theoretical) would be approximately 19 kJ/g. If the same measurements were conducted under typical fire conditions for wood, we would measure ΔH_c of approximately 12–15 kJ/g for the flaming period and ΔH_c of approximately 30 kJ/g for the smoldering phase of the char.

6.4.2 Heat of Combustion of Wood

It should be appreciated that the g (grams) in kJ/g is the mass of the fuel being reacted. For example, if about 70% of the wood turns to fuel gas, and the remaining 30% burns as char, then as energy must be conserved, using 14 kJ/g for the heat of combustion of the fuel gas, and 30 kJ/g for that in smoldering:

$$(14\ \text{kJ/g gas})(0.7\ \text{gas/wood}) + (30\ \text{kJ/g char})(0.3\ \text{char/wood}) = 18.8\ \text{kJ/g wood}$$

This shows how wood releases its energy in two stages: flaming and smoldering. The process is illustrated in Figure 6.8 for a typical wood-like material. It corresponds to the mass loss in Figure 6.5. In the figure, the power per unit area reaches a peak at about 20 seconds just after ignition. This is followed by surface charring, insulating the heat flux, and the power. A second peak occurs as the virgin wood becomes thermally thin and its backside insulation reduces heat conduction. So more energy stays in the thin wood and its power rises again, but eventually it falls again as the virgin wood is expended. But now the remaining char structure smolders beginning at 380 seconds. The heat of combustion measured as well during the periods of flaming and smoldering clearly shows an average heat of combustion during flaming of about 12–14 kJ/g and about 30–35 kJ/g during smoldering. This heat of combustion was determined by dividing the measured energy by the mass loss in a controlled experiment.

As the char layer builds, flaming will eventually cease at a mass loss flux of about 2 g/m^2-s or less. In the data of Figure 6.8, flaming ceases at about 50 kW/m^2 and the heat of combustion at that time is about 20 kJ/g. This gives a mass flux at extinction of 2.5 g/m^2-s. Smoldering then consumes the char by oxidation has a decreasing burning flux of 1.5 to about 0.5 g/m^2-s. At the peak burning condition in Figure 6.8, the wood achieves about 17 g/m^2-s (260 kW/m^2/15 kJ/g).

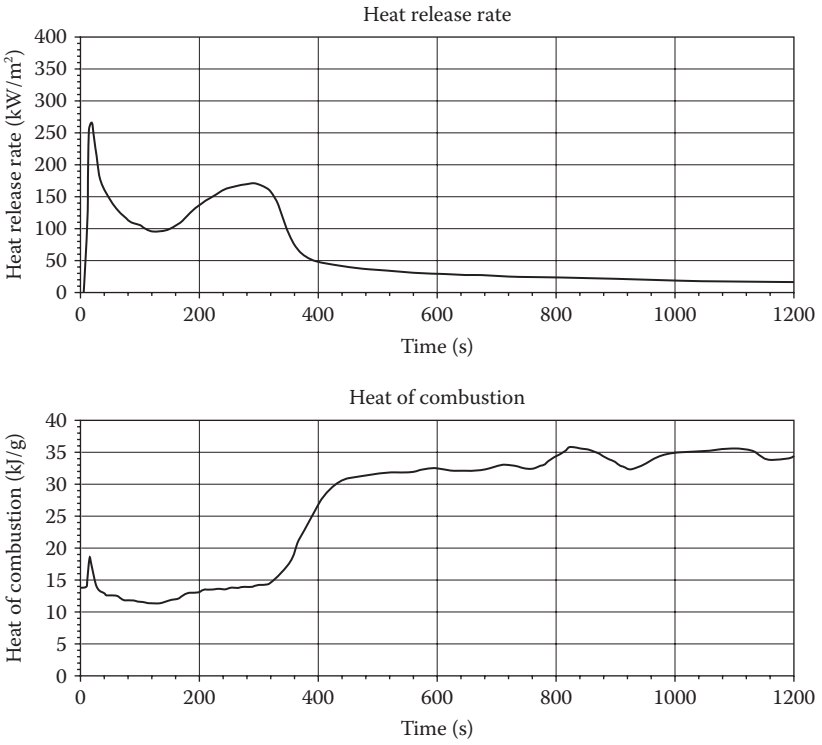

FIGURE 6.8
Heat release rate and corresponding heat of combustion for wood burning horizontally under and external radiant heat flux of 50 kW/m². (From Dillon, S.E. et al., Determination of properties and the prediction of the energy release rate of materials in the ISO 9705 room-corner test, NIST-GCR-98-753, NIST, Gaithersburg, MD, June 1998.)

6.4.3 Heats of Combustion of Materials

In this chapter, we are primarily concerned about the effective heat of combustion during the flaming period. In general, both the production of char and the formation of incomplete products of combustion such as soot and carbon monoxide reduce the heat of combustion during flaming. Chemical additives—retardants—can also play a role here to reduce the heat of combustion. That is why ΔH_c must be measured for a specific material to be accurate. The effective heats of combustion during flaming tend to be highest for gas and liquid fuels, and least for char formers. Table 6.3 lists typical values.

6.4.4 Heat Release Parameter

An important parameter in assessing fire hazard is the ratio of $\Delta H_c/L$. This has been termed the *Heat Release Parameter, HRP*. It is important because HRP expresses the combustion energy released per energy required to vaporize

TABLE 6.3

Energy Release Properties of Materials

Polymers	Heat of Combustion, ΔH_c (kJ/g)	HRP, $\Delta H_c/L$ (—)
Gases		
Methane	50.0	—
Ethane	47.5	—
Ethene	50.4	—
Propane	46.5	—
Carbon monoxide	10.1	—
Liquids		
n-Butane	45.7	118
n-Hexane	43.8	97
Heptane	44.6	89
Gasoline	43.7	135
Kerosene	43.2	65
Benzene	40.0	75
Acetone	30.8	49
Ethanol	26.8	27
Methanol	19.8	27
Ordinary polymers		
High-density polyethylene, HDPE	40.0	21
Polyethylene, PE	43.4	37
Polypropylene, PP	44.0	32
Polystyrene, PS	35.8	17
Nylon	27.9	30
Nylon 6	28.8	21
Polyoxymethylene, POM	13.4	6, 13
Polymethylmethacrylate, PMMA	24.2	12
Polybutylene terephthalate, PBT	20.9	23
Acrylonitrile–butadiene–styrene, ABS	30.0	14, 21
ABS-FR	11.7	4
Polyurethane, PU foam	18.4	19
Polyvinylchloride, PVC	9–11	3, 6
Chlorinated PVC	5.8	1
Polyester/glass fibers (30%)	16.0	6
Polyvinyl ester	22.0	13
Epoxy	25.0	11
Epoxy/glass fibers (69%)	27.5	2
High-temperature polymers and composites		
Polycarbonate, PC	21.9	5, 21
Cross linked polyethylene (XLPE)	23.8	5
Polyetheretherketone, PEEK/glass fibers (30%)	20.5	7
Phenolic/glass fibers (45%)	22.0	5

(*Continued*)

TABLE 6.3 (*Continued*)

Energy Release Properties of Materials

Polymers	Heat of Combustion, ΔH_c (kJ/g)	HRP, $\Delta H_c/L$ (—)
Wood		
Douglas fir	14.7	1–2
Hemlock	13.3	1.5–3
Plywood	11.9	1.6
Plywood, FR	11.2	1.2
Chipboard, FR	9.2	0.9
Textiles		
Wool	19.5	5
Acrylic fiber	27.5	6
Composites		
Paper on gypsum	6.4	1.3
Wallpaper on rigid PU	18.9	3.4

Sources: Dillon, S.E. et al., Determination of properties and the prediction of the energy release rate of materials in the ISO 9705 room-corner test, NIST-GCR-98-753, NIST, Gaithersburg, MD, June 1998; Tewarson, A., Flammability of polymers, Chap. 11 in: Andrady, A.L., ed., *Plastics and the Environment*, John Wiley & Sons, Inc., Hoboken, NJ, 2003; Panagiotou, J. and Quintiere, J. G., Generalizing the flammability of materials, in: *Proceedings of the 10th International Conference on Interflam 2004,* Interscience Communication, London, U.K., 2004, pp. 895–906.

the fuel. The HRP values are also listed in Table 6.3. As seen from the table, the HRP values range from about 1 to 100, as materials move from char formers to liquid fuels. This is a tremendous difference. It can be seen that liquid fuels are comparably more dangerous than solid fuels, as they will produce much more HRR for a given area burning. The HRP is an indicator of hazard for a material, as a high value implies a lot of energy is released or little energy is required to cause burning. Materials that have a HRP lower than about 3 are not likely to burn since only a portion of the energy released is transferred back to the fuel. Most of the energy is transported away in the buoyant flow, and some is lost to the surroundings by radiation.

6.5 Estimating Energy Release Rate

Example 6.2

Compute the mass loss rate per unit area and the energy release rate for a 1 m diameter pool fire of wood, polystyrene, heptane, and gasoline. Treat the wood as a crib, not a flat slab. Assume the maximum burning rate per unit area applies for these relatively large pool fires. Figure 6.9 depicts the dynamic feature of this pool fire example.

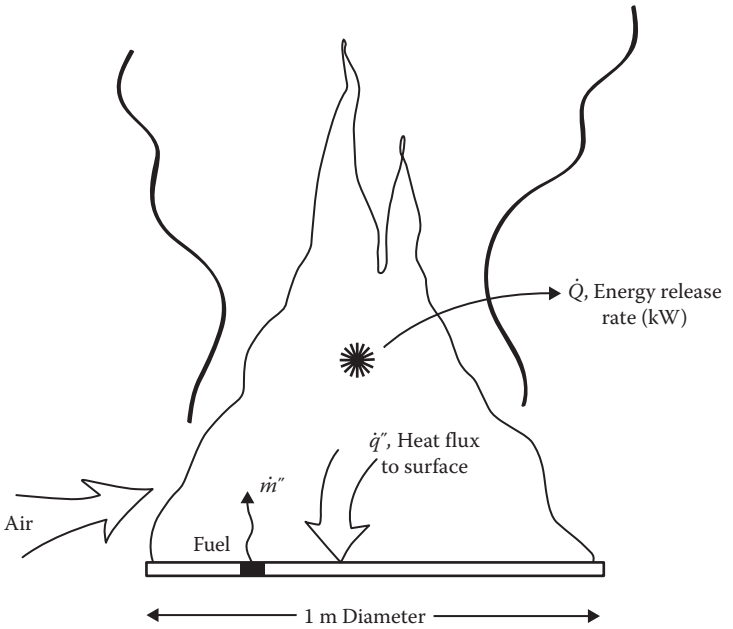

FIGURE 6.9
Example configuration as a pool fire and its dynamics of burning. (*Note*: Fuel vapor near surface can block heat and reduce $\dot{q}''$.)

1. *Wood*. From Table 6.2 for wood cribs, the maximum burning flux is $\dot{m}'' = 11\ \text{g/m}^2\text{-s}$. (*Note*: If this were actual wood cribs or stacked pallets, we would have to consider the exposed surface. Instead, here we consider only a top surface representing a shallow array.)

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(1\ \text{m})^2 = 0.785\ \text{m}^2$$

$$\dot{Q} = \dot{m}''A\Delta H_c$$

$$= (11\ \text{g/m}^2\text{-s})(0.785\ \text{m}^2)(15.0\ \text{kJ/g})$$

$$= 130\ \text{kJ/s} = 130\ \text{kW}$$

2. *Polystyrene*. Table 6.2 gives for a granular fuel

$$\dot{m}'' = 38\ \text{g/m}^2\text{-s}$$

$$\dot{Q} = \dot{m}''A\Delta H_c$$

$$= (38\ \text{g/m}^2\text{-s})(0.785\ \text{m}^2)(39.85\ \text{kJ/g})$$

$$= 1189\ \text{kW}$$

3. *Heptane*. Table 6.2 gives 65–75 g/m²-s for the maximum mass flux. Therefore, we see some differences that must depend on the source of the data. We will use the higher value, 75 g/m²-s.

$$\dot{Q} = (75\ \text{g/m}^2\text{-s})(0.785\ \text{m}^2)(44.6\ \text{kJ/g})$$
$$= 2626\ \text{kW}$$

4. *Gasoline*. Again, using Table 6.2 we find 55 g/m²-s.

$$\dot{Q} = \dot{m}''A\Delta H_c$$
$$= (55\ \text{g/m}^2\text{-s})(0.785\ \text{m}^2)(43.7\ \text{kJ/g})$$
$$= 1887\ \text{kW}$$

Summary for 1 m diameter pool fires.

	$\dot{m}''$ (g/m²-s)	$\dot{Q}$ (kW)	HRP (–)
Wood	11	130	1–2
Polystyrene	38	1189	17
Heptane	75	2650	89
Gasoline	55	1887	135

These results are very illustrative of the relative potential for damage of these four fuels. Despite their relatively small area (1 m diameter), the liquid fuels would present fires that can rapidly bring typical residential rooms to full involvement. The polystyrene would also pose a serious threat, but the wood at this size would be a manageable fire.

A relatively low net heat flux of 19 kW/m² is causing the gasoline fire compared to 70 kW/m² for the polystyrene fire. These heat flux values can be computed from Equation 6.1 and Table 6.1 and are listed in Table 6.2. The difference in these heat fluxes accentuates our lack of understanding in how to predict them from theory. Their difference is almost counterintuitive, because the gasoline fire is larger in power, $\dot{Q}$. One explanation suggests these differences are due to radiation absorption. The large amount of vaporized gasoline by-products near the fuel surface acts like a cloud in blocking the flame radiation.

Tables 6.2 and 6.3 provide a very practical way to estimate burning rate and firepower for a number of common fuels in a horizontal orientation. It gives an upper bound and is likely very accurate for fires above 1 m in diameter. More data can be obtained in the literature. For a vertical orientation, using a flame heat flux of about 25 kW/m² can be a starting point with Equation 6.1.

The method of computing the firepower and burning rate for materials is limited. It is for a static fire. It does not address a real object. In principle, it is possible to synthesize the actions of ignition, flame spread, and burning on horizontal and vertical surfaces to represent a real object. In practice, this is impractical. An object ignited and spreading to its full involvement is difficult to compute from first principles.

6.6 Experimental Firepower (HRR) Results for Selected Items

The only practical way to determine the burning rate or energy release rate of an item is by direct measurement. This measurement depends on the manner of ignition, particularly for the initial fire growth over time. Weighing devices or load cells can be used to determine mass loss while an item is burning. If the products of combustion are collected in an exhaust duct and the oxygen content of these gases is measured, the energy release rate can also be determined. Such a device is called an "oxygen consumption calorimeter" (Figure 6.10). The device works on the principle that the heat of combustion per unit mass of oxygen consumed is nearly a constant (13 kJ/g) for a wide range of ordinary fuel compounds. The energy release rate is found directly from recording the rate of oxygen consumed. This type of device is available in many forms. Some can measure small material samples, others are very large devices that might contain a small house. Figure 6.11 shows a large item being burned at the SP Technical Research Institute of Sweden. The products of combustion are fully collected in the hood, and they are measured for oxygen consumption in the exhaust. The firepower (kW) is computed as 13 kJ/g times the consumption rate of oxygen (g/s).

Typical examples of results for upholstered furniture are shown in Figure 6.12. Typically, the early part of the growth curve depends on the ignition process. The steep increase in $\dot{Q}$ is due to the overall fire growth—flame spread and burning rate—for the furniture. The decay from the peak energy release rate reflects the *burnout* of various portions of the furniture. The width of the curves, or more precisely, the area under them, represents the amount of burnable fuel (in joules, J). The amount of burnable fuel or available energy is responsible for the duration of the fire. Duration is just as important as the peak power of the item. Indeed, duration of building fires is responsible for the response of structure to the fire. The longer a fire burns, the more the structure can be heated. At a critical temperature, the structure can fail.

The simplest way to estimate energy release is to measure mass loss rate by burning an object on a scale. From Equation 6.2, the $\dot{Q}$ is found by multiplying this mass loss rate by an appropriate heat of combustion. Table 6.4 gives some typical peak values of burning rate for real items along with very rough estimates of their peak energy release rates. These are presented to primarily illustrate the spectrum of firepower, not for precise generic use.

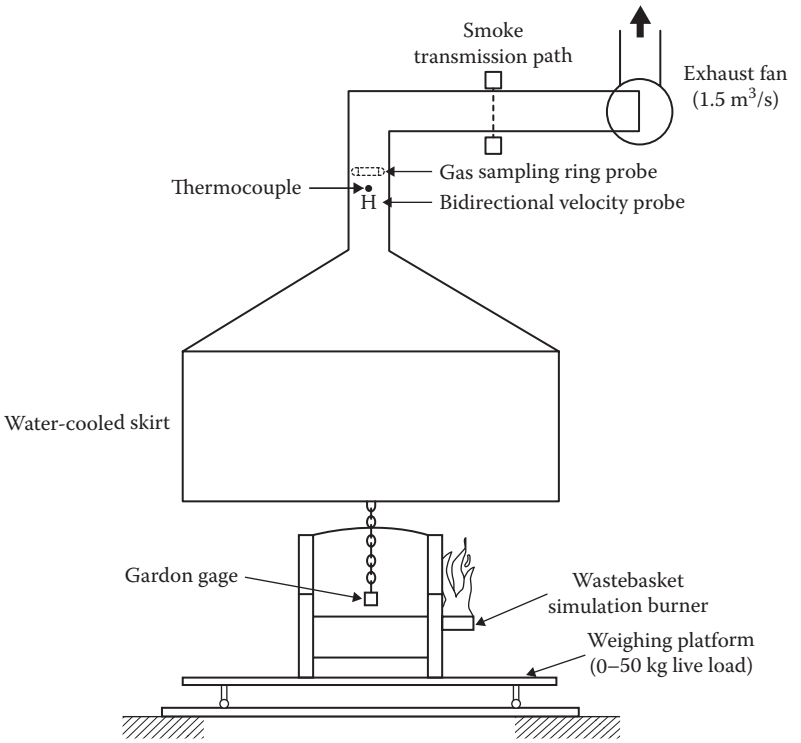

FIGURE 6.10
The furniture calorimeter. (Reprinted with permission from Babrauskas, V., Burning rates, Chap. 3-1 , in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.)

Figures 6.12 through Figure 6.22 give experimental results for a range of items, including trash, televisions, Christmas trees, upholstered chairs, and pallets. Again their peak value and their duration are both important. Such data are important for making estimates of how typical furnishing can affect fire growth. Starting with one object, its interaction with another object can be addressed. For example, we know it takes time to ignite. If one of these items were to ignite another object, it would have to impose a sufficient heat flux for a sufficient time. From Chapter 3, knowing the firepower can give the radiant heat flux to the surroundings. Knowing the ignition properties of the next object can provide a means to assess the potential for ignition. Such a calculation can tell if the first fire is capable of spreading to other furnishings. Of course, it must be emphasized that these data in Figures 6.12 through 6.22 are specific. They may be used as generic representations, but each object is specific. The data depend not just on the properties of the object but also on how it was ignited, as that ignition likely controlled the early rate of spread.

FIGURE 6.11
Sofa burning in a large calorimeter. (Courtesy of SP Technical Research Institute of Sweden, Borås, Sweden.)

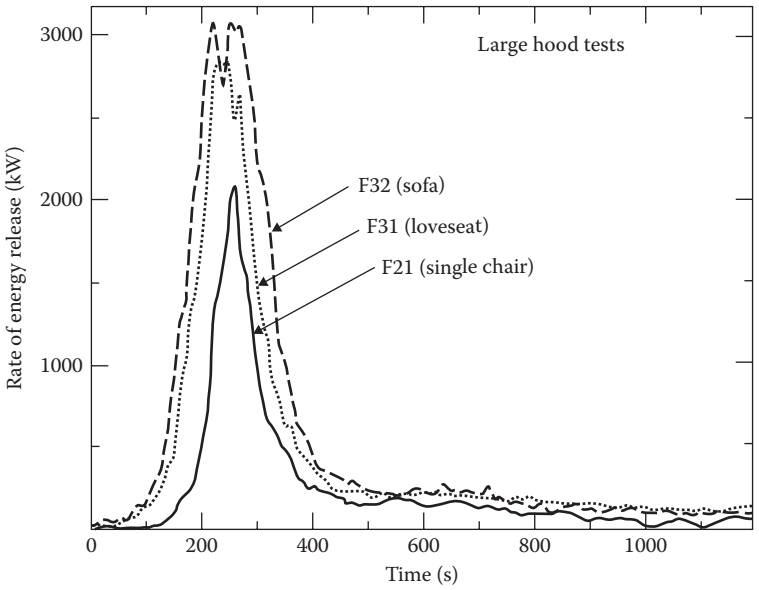

FIGURE 6.12
Typical upholstered chair energy release rates. (Reprinted from Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995. With permission.)

TABLE 6.4

Typical Peak Burning Rate and Firepower Values

Generic Item	Estimated Burn Rate (g/s)	Estimated Firepower (kW)
Small waste containers (18–40 L)	3–6	100
Large waste containers (70–120 L)	5–10	300
Chairs, wood and upholstered	10–60	1200
Sofas	20–100	2000
Beds	20–140	2500
Closet	~40	1000
Office	~90	2300
Bedroom	~130	3300
Kitchen	~190	4800
House	~30,000	750,000

Source: Based on data from Quintiere, J., Growth of fire in building compartments, in: Robertson, A.F., ed., *Fire Standards and Safety*, ASTM STP 614, American Society for Testing and Materials, West Conshohocken, PA, 1977, pp. 131–167.

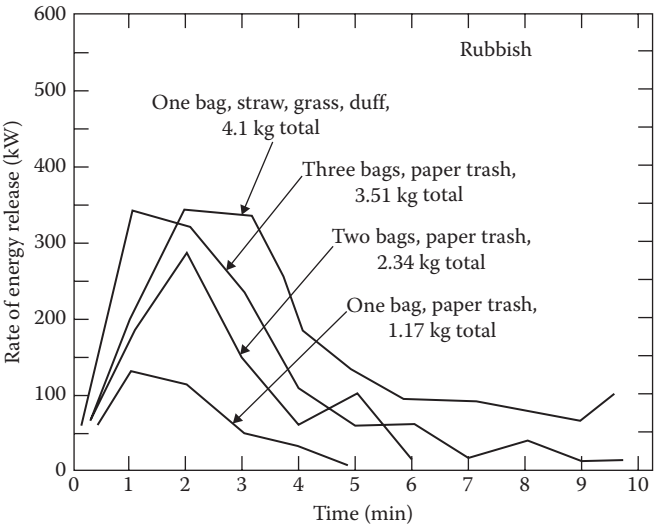

FIGURE 6.13
Energy release rate of representative rubbish. (Reprinted from Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995. With permission.)

These results (Figures 6.12 through 6.22) show the variation in burning behavior within the category of a single generic item. This variation can be due to many factors: size, materials, nature of the ignition source, and the effect of fire retardants. As with Table 6.4, they represent a range of typical values. To accurately know how an item will burn, it must be tested in a device similar to that shown in Figure 6.10.

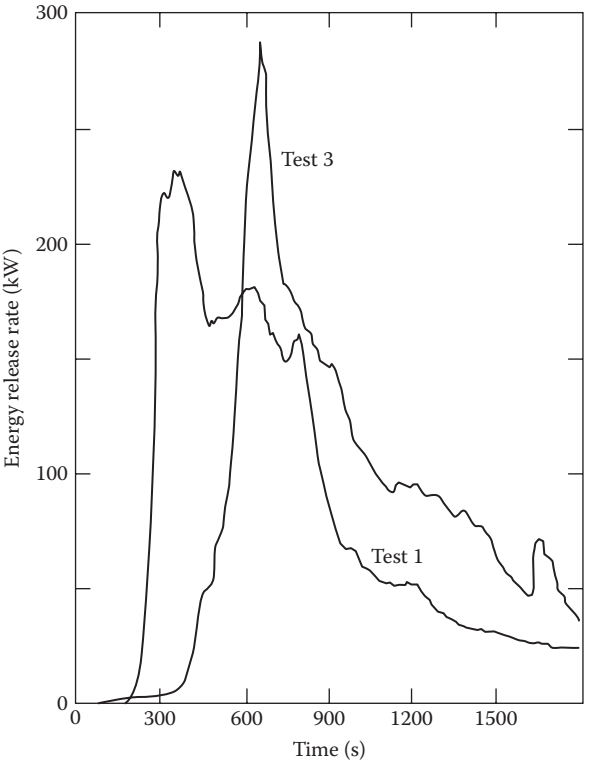

FIGURE 6.14
Energy release rate results for television sets. (Reprinted from Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995. With permission.)

Table 6.5 gives typical experimental values for warehouse commodities in terms of their floor area (A) covered. These firepower (HRR) values per unit area, $\dot{Q}''$ should be interpreted as peak average values for a fixed floor area covered. Their duration of burning (t_b) can be found by knowing the total mass (m) available to burn:

$$t_b = \frac{m\Delta H_c}{\dot{Q}''A} \tag{6.4}$$

By putting the average peak power together with the burn time, we can construct a very approximate rendition of the power curves for a particular object. In the next section, we will see how this construction can be perhaps improved.

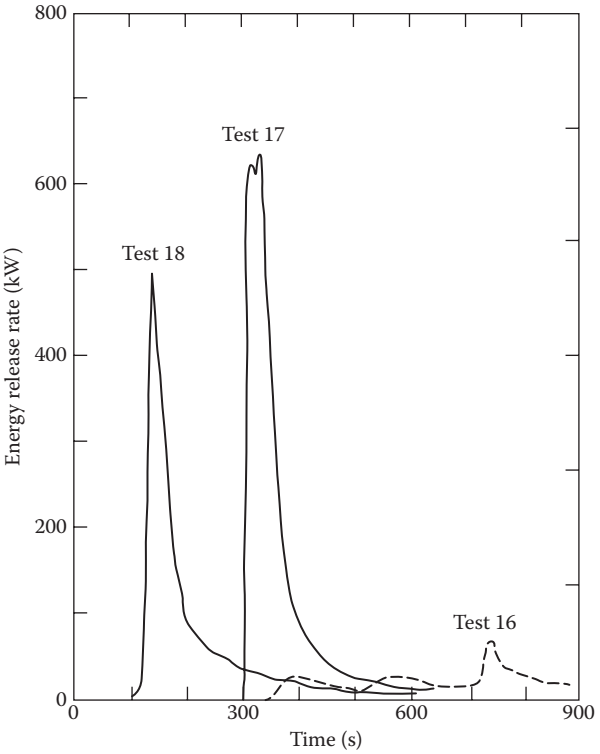

FIGURE 6.15
Energy release rate results for Christmas trees. (Reprinted from Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995. With permission.)

6.7 Fire Growth Rate

As we have seen, the fire growth rate depends on the ignition process; flame spread, which defines its perimeter; and the mass burning flux over the area involved. For items of furniture and commodities, this complex process cannot be predicted by simple formulas. However, each item, due to its composition and configuration, must have a characteristic growth time. In other words, a given item, once ignited, may achieve 1 MW (megawatt, a million watts) in say 130 seconds. For another object, it might take 80 seconds. Such data have been compiled and are useful in fire analyses. Also it has been found that the growth rate approximately follows a relationship proportional to time squared. Considering the flame spread velocity as constant over time can provide an explanation for this time-squared behavior. Then, the fire area would grow as t^2 (length is velocity times time, and area is related to length squared).

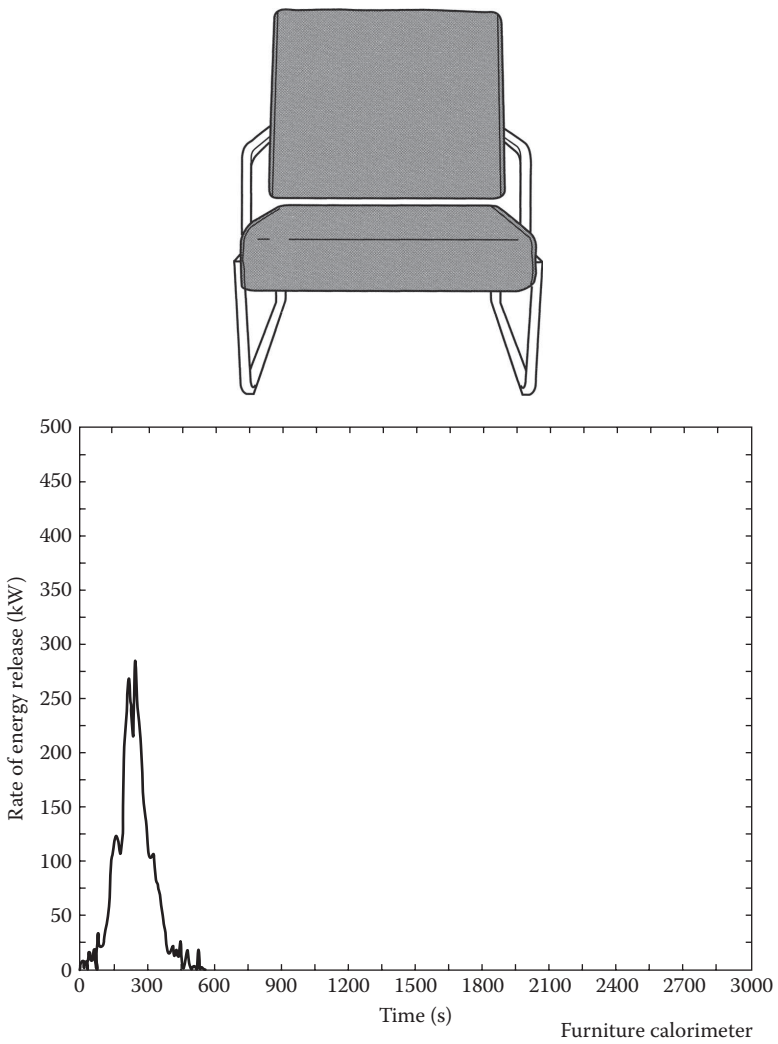

FIGURE 6.16
Upholstered chair. (After Gross, D., Data sources for parameters used in predictive modeling of fire growth and smoke spread, NBSIR 85-3223, National Bureau of Standards, Gaithersburg, MD, September 1985.)

Alternatively, if the rate of fire growth depends on the fire itself, the growth rate would be exponential (e^t), not t^2. Both of these growth rates have been suggested for the early fire growth. But the t-squared relationship is simplest and it seems to work well. The empirical growth rate formula commonly used is

$$\dot{Q} = at^2 \tag{6.5}$$

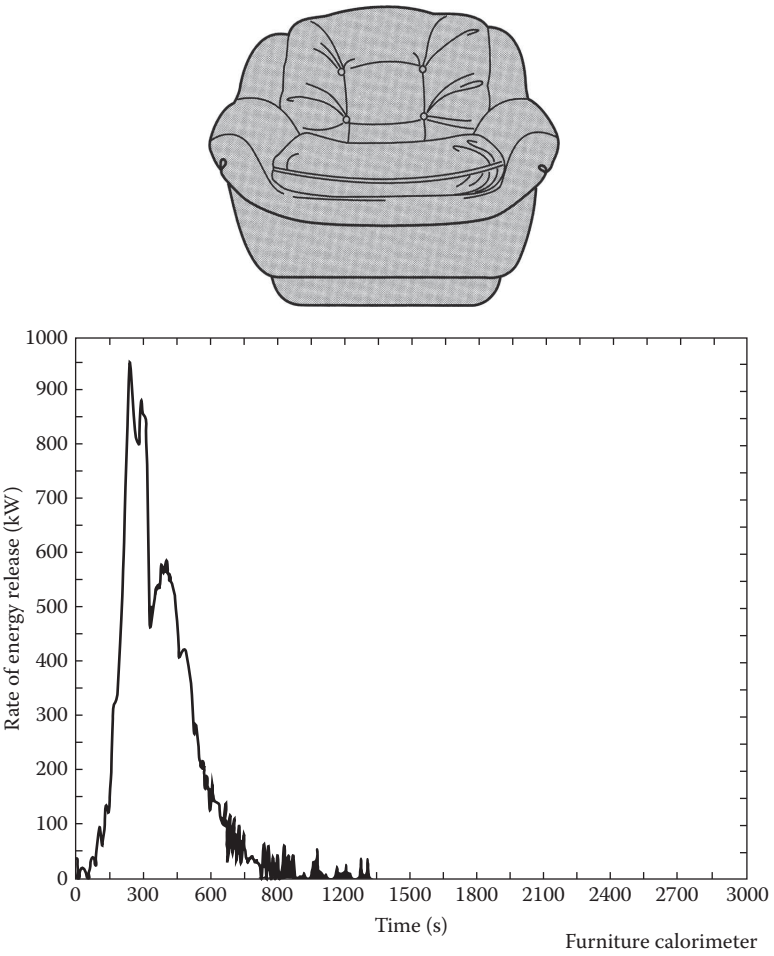

FIGURE 6.17
Upholstered chair. (After Gross, D., Data sources for parameters used in predictive modeling of fire growth and smoke spread, NBSIR 85-3223, National Bureau of Standards, Gaithersburg, MD, September 1985.)

where a is a constant associated with the item. If t_1 is the characteristic time to reach 1 MW, then $a = 1\ \text{MW}/t_1^2$

and

$$\dot{Q} = \left(\frac{t}{t_1}\right)^2 \tag{6.6}$$

This growth rate expression has been fitted to experimental data by ignoring the early incubation period where the growth process is establishing a

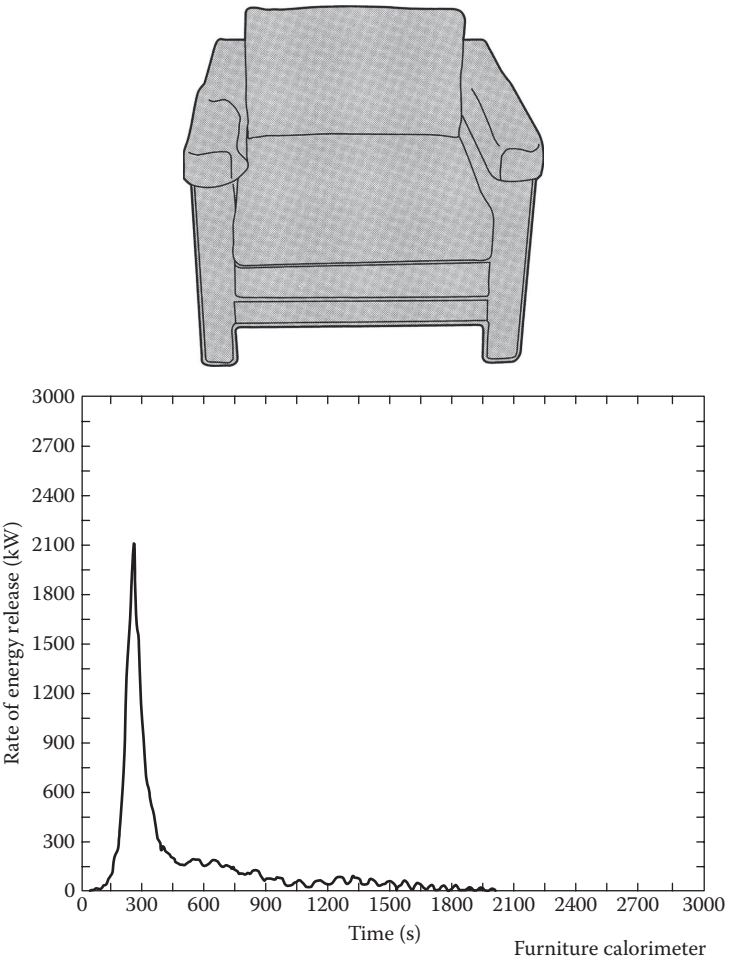

FIGURE 6.18
Upholstered chair. (After Gross, D., Data sources for parameters used in predictive modeling of fire growth and smoke spread, NBSIR 85-3223, National Bureau of Standards, Gaithersburg, MD, September 1985.)

foothold. This incubation period is most likely due to spurious flame spread and the nature of the ignition process. The t^2 fit is illustrated in Figure 6.23, along with an illustration of the incubation time. The precise incubation time is impossible to predict. However, it can be of significance if one is using the *t*-squared growth rate to estimate the time for detection. Detection may have occurred during the incubation growth period.

Table 6.6 lists fire growth times to 1 MW (t_1) corresponding to t^2 fires for commodities that have unlimited lateral extent for growth. In reality, at some point, the decay process must occur as indicated by the burning curves shown in Figures 6.12 through 6.22. In other words, Table 6.6 gives

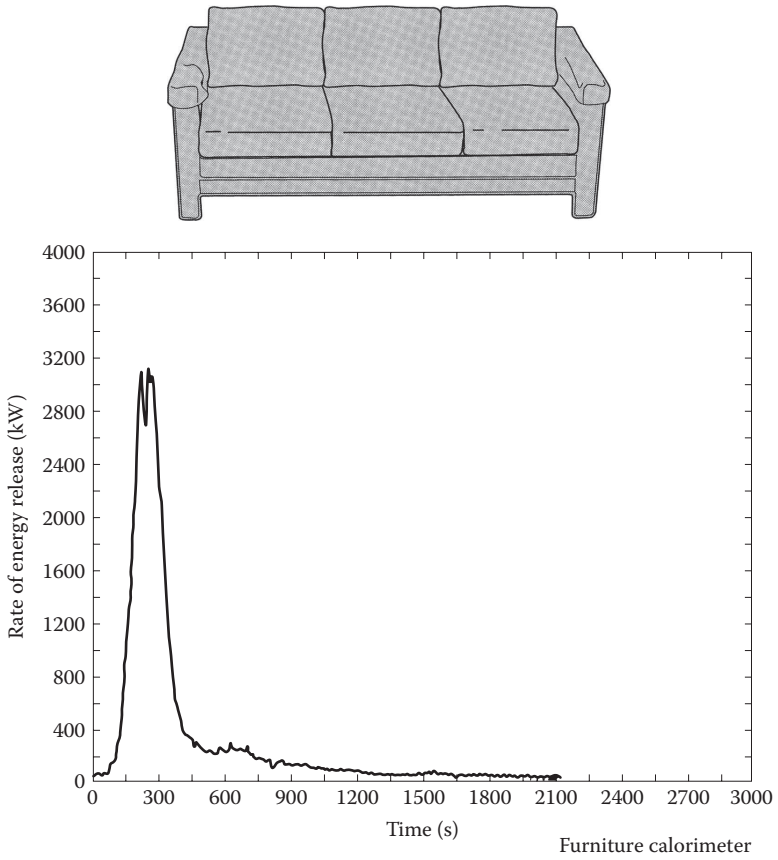

FIGURE 6.19
Sofa. (From Gross, D., Data sources for parameters used in predictive modeling of fire growth and smoke spread, NBSIR 85-3223, National Bureau of Standards, Gaithersburg, MD, September 1985.)

the growth time; then for a given area of that fuel item, Table 6.5 would give its peak power. In principle, the process of estimating the growth rate of an actual item using the *t*-squared behavior can be done from Equations 6.3 and 6.4 and Tables 6.5 and 6.6.

Example 6.3

Consider 18 ft² of wood pallets stacked 5 ft high. Let us construct a fire-power graph. From Table 6.6, t_1 is 97–187 seconds. Take t_1 = 100 s as a representative value for illustration. Using Equation 6.5:

$$\dot{Q} = \left(\frac{t(\text{s})}{100} \right)^2 \text{MW}$$

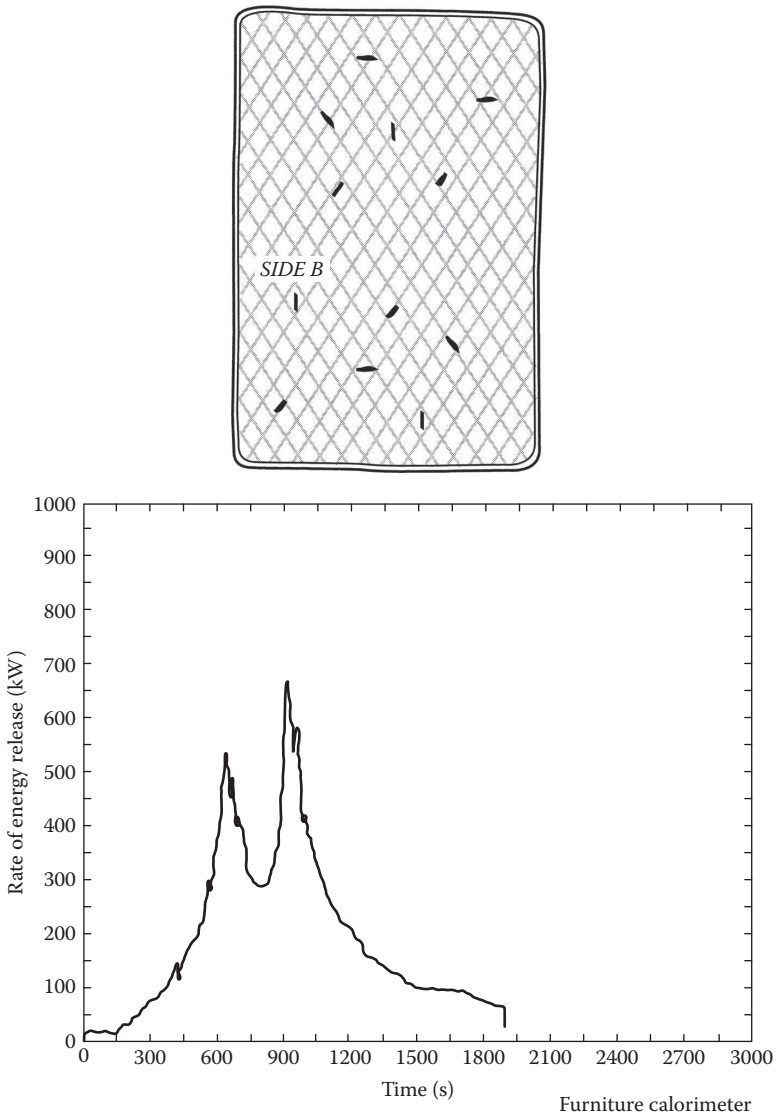

FIGURE 6.20
Mattress. (From Gross, D., Data sources for parameters used in predictive modeling of fire growth and smoke spread, NBSIR 85-3223, National Bureau of Standards, Gaithersburg, MD, September 1985.)

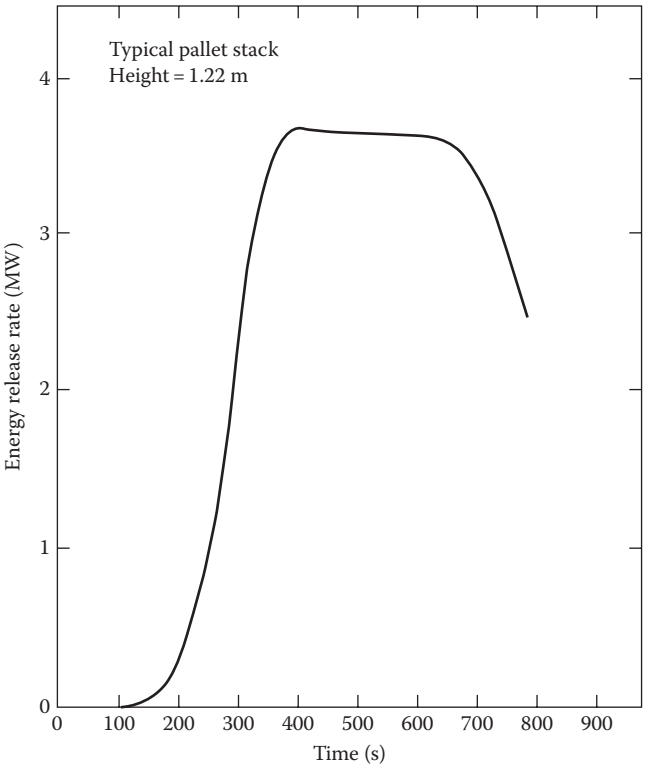

FIGURE 6.21
Typical energy release rate for a wood pallet stack. (Reprinted from Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995. With permission.)

From Table 6.5, the peak energy release rate is computed as

$$\dot{Q} = (3.7\ \text{MW/m}^2) \times (18\ \text{ft}^2 \times 0.0929\ \text{m}^2/\text{ft}^2) = 6.19\ \text{MW}$$

It will take a time to reach this level. It can be computed by equating the firepower:

$$t_{grow} = 100 \times (6.19)^{1/2} = 249\ \text{s}$$

The duration of this fire will depend on how much wood is available in the pallet stack. Suppose the pallets weighed 200 kg, and the wood heat of combustion is 15 kJ/g. The available energy to consume would be 200 kg × 15 MJ/kg = 3000 MJ. This entire pile would burn

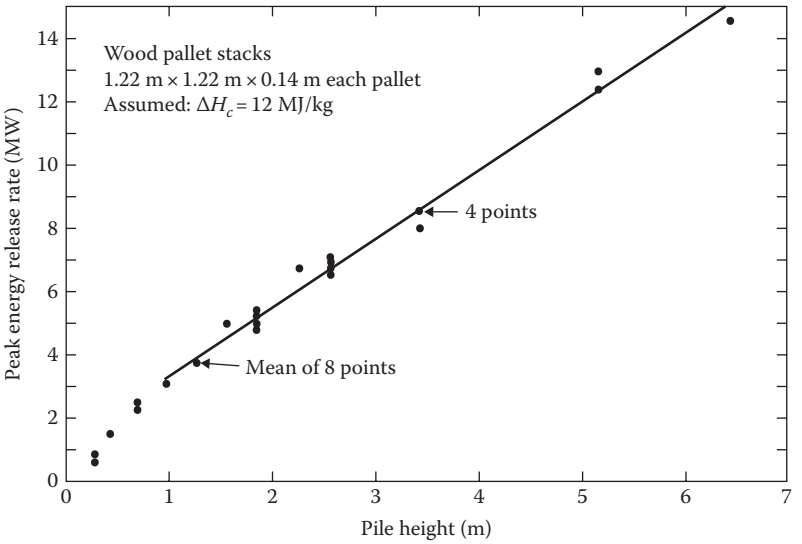

FIGURE 6.22
Dependence of pallet burning rate on stack height. (Reprinted from Babrauskas, V., Burning rates, Chap. 3-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995. With permission.)

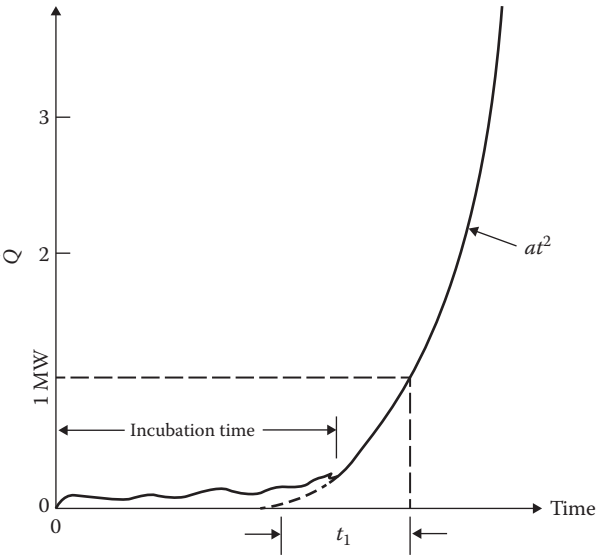

FIGURE 6.23
Fire growth rate curve of t^2 fitted to data. (From Heskestad, G., Venting practices, Sect. 6, Chap. 10 in: Cote, A.E. and Linville, J.L., eds., *Fire Protection Handbook*, 17th edn., National Fire Protection Association, Quincy, MA, 1991, pp. 6.104–6.116.)

TABLE 6.5

Fire Behavior of Warehouse Commodities: Fully Involved Energy Release Rates for a Fixed Floor Area

Commodity	$\dot{Q}$/Floor Area Covered (MW/m^2)
Methanol	0.72
Diesel oil	1.9
Kerosene	2.2
Gasoline	2.2
Wood pallets, stacked 1½ ft high	1.3
Wood pallets, stacked 5 ft high	3.7
Wood pallets, stacked 10 ft high	6.6
Wood pallets, stacked 15 ft high	9.9
Mail bags, filled, stored 5 ft high	0.39
PE letter trays, filled, stacked 5 ft high	8.2
PS insulation board, rigid foam, stacked 14 ft high	3.1
PU insulation board, rigid foam, stacked 15 ft high	1.9
PS tubs rested in cartons, stacked 14 ft high	5.1
FRP shower stalls in cartons, stacked 15 ft high	1.2
PE bottles in cartons, stacked 15 ft high	1.9
PS toy parts in cartons, stacked 15 ft high	2.0
PE trash barrels in cartons, stacked 15 ft high	2.9
Cartons, compartmented, stacked 15 ft high	2.2
PVC bottles packed in cartons, compartmented, stacked 15 ft high	3.3
PP tubs packed in cartons, compartmented, stacked 15 ft high	4.2
PE bottles packed in cartons, compartmented, stacked 15 ft high	6.1
PS jars packed in cartons, compartmented, stacked 15 ft high	14.0

Source: Based on data from Heskestad, G., Venting practices, Sect. 6, Chap. 10 in: Cote, A.E. and Linville, J.L., eds., *Fire Protection Handbook*, 17th edn., National Fire Protection Association, Quincy, MA, 1991, pp. 6.104–6.116.

Notes: PE, polyethylene; PU, polyurethane; PVC, polyvinyl chloride; PS, polystyrene; PP, polypropylene; FRP, fiberglass-reinforced polyester.

in about 485 seconds (3000 MJ/6.19 MJ/s). Here, no account of the energy consumed during the *t*-squared growth period was included in the previous time estimate. To do so would involve some calculus. If that were done the actual burnout time would be about 650 seconds following ignition. The constructed graph is shown in Figure 6.24. It starts as *t*-squared, reaches the maximum of 6.19 MW at 249 seconds, and burns out at 650 seconds.

TABLE 6.6

Characteristic Times to Reach 1 MW for t^2 Fires

Commodity	t_1 (s)
Wood pallets, stacked 1½ ft high	155–310
Wood pallets, stacked 5 ft high	92–187
Wood pallets, stacked 10 ft high	77–115
Wood pallets, stacked 16 ft high	72–115
Mail bags, filled, stored 5 ft high	187
Cartons, compartmented, stacked 15 ft high	58
Paper, vertical rolls, stacked 20 ft high	16–26
Cotton, polyester garments in 12 ft high rack	21–42
"Ordinary combustibles" rack storage, 15–30 ft high	39–262
Paper products, densely packed in cartons, rack storage, 20 ft high	461
PE letter trays, filled, stacked 5 ft high on cart	189
PE trash barrels in cartons, stacked 15 ft high	53
PE bottles packed in compartmented cartons, 15 ft high	82
PE bottles in cartons, stacked 15 ft high	72
PE pallets, stacked 3 ft high	145
PE pallets, stacked 6–8 ft high	31–55
PU mattress, single, horizontal	115
PU insulation board, rigid foam, stacked 15 ft high	7
PS jars packed in compartmented cartons, 15 ft high	53
PS tubs nested in cartons, stacked 15 ft high	115
PS insulation board, rigid foam, stacked 14 ft high	6
PUS bottles packed in compartmented cartons, 15 ft high	8
PP tubs packed in compartmented cartons, 15 ft high	9
PP and PE film in rolls, stacked 14 ft high	38
Distilled spirits in barrels, stacked 20 ft high	24–39

Source: Based on data from Heskestad, G., Venting practices, Sect. 6, Chap. 10 in: Cote, A.E. and Linville, J.L., eds., *Fire Protection Handbook*, 17th edn., National Fire Protection Association, Quincy, MA, 1991, pp. 6.104–6.116.

Note: PE, polyethylene; PU, polyurethane; PVC, polyvinyl chloride; PS, polystyrene; PP, polypropylene; FRP, fiberglass-reinforced polyester.

6.7.1 NFPA Design Categories

The t^2 relationship has proved useful and has been adopted into NFPA 92B[12] for design of smoke control systems. These NFPA standards classify the growth times as follows and as illustrated in Figure 6.25:

Slow	$t_1 = 600$ s
Medium	$t_1 = 300$ s
Fast	$t_1 = 150$ s
Ultrafast	$t_1 = 75$ s

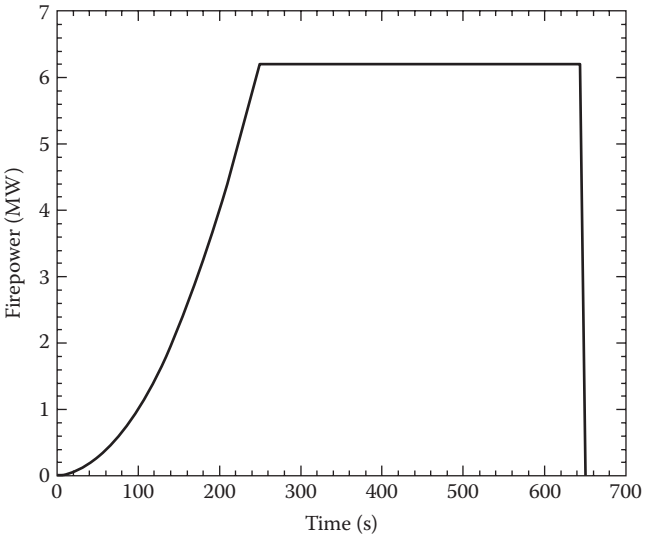

FIGURE 6.24
Example of fire growth rate constructed for wood pallets.

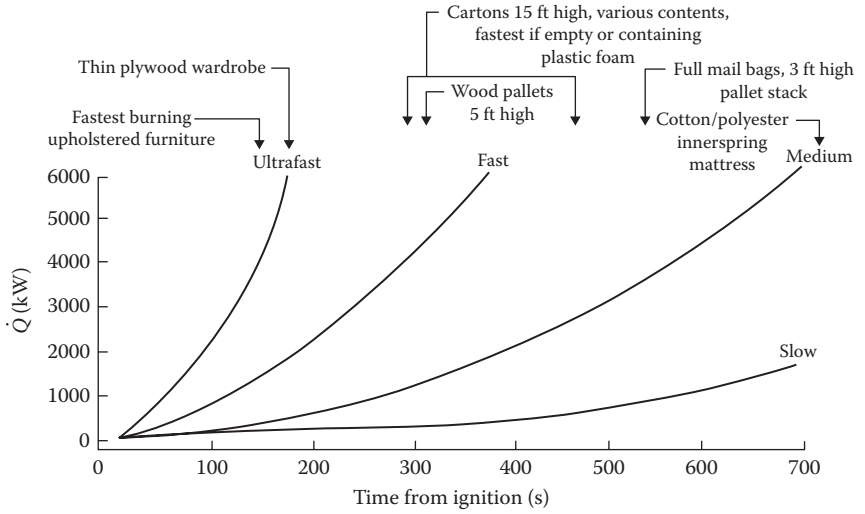

FIGURE 6.25
Categories of t^2 fires. (Reprinted from Guide for smoke management systems in malls, atria, and large areas, National Fire Codes, Vol. 10, NFPA 92B, 1991 edn., National Fire Protection Association, Quincy, MA, p. 92B-30, 1995. With permission.)

These categories are only for rough guidance and perhaps standardization in design. They should not be used to hypothesize fire growth without a suitable basis. The growth rate must be established by relevant data as in Table 6.6. As the previous example illustrated, a practical application to construct the entire growth and decay process must use data such as that in Tables 6.5 and 6.6. The early growth can be considered as t^2 up to the full involvement, and then burning ceases when the available mass of fuel is depleted. However, the fire does not necessarily stop abruptly as in Figure 6.24. This abrupt ending can be refined.

6.7.2 Fire HRR of Item Constructed

Recently, Natori[13] has compiled and correlated burning items in a systematic form. These data include furnishings, appliances, pine trees (dry), and others items tabulated completely in a working group document of Japan. Some selected results are summarized here in Table 6.7. The burning of the items can be represented in the form of a *t*-squared growth to a steady maximum and followed by a *t*-squared decay. Mathematically this is expressed in terms of a, for growth, and a_d for decay, to best represent the experimental data on energy release rate of the item. This format is shown in Figure 6.26. The decay is shown to follow a decreasing *t*-squared behavior. The form of this power curve has been successfully fitted to a large assortment of data. Table 6.7 contains some of these data. The values of the parameters from Figure 6.26 are listed in the table. Because up to 25 items of a given class have been included in the data, there is a distribution in the results of a given class. For example, the peak power of a sofa could reach 1826 kW on average with a standard deviation of 676 kW. All the parameters are given by a mean and deviation. This shows the variability in a given class, and that one cannot generalize data for a single sofa as precise for a class of sofas. (In Table 6.7 for the dry [Christmas] trees, the total heat release [THR] is given in MJ instead of the time for peak burning [t_{max}].)

It may be somewhat more sophisticated to use these detailed data of Table 6.7, but they represent the burning process more completely. By the variations in Table 6.7, it should be obvious that such data can only be used as representative, and not definitive. For the HRR of a specific item, a calorimeter test must be made. Then, it is very likely the results can be tabulated as in the form of Table 6.7. For rough approximations of any item, Natori[13] recommends some simple formulas that have been correlated in terms of mass and area. She defines a cylindrical surface area (A_b) encompassing the item's overall diameter (D) and height (H). Also its encompassing volume is designated as V_b. Then a is given in terms of bulk density (ρ_b = Mass/V_b in kg/m^3) as

$$a\ (\text{kW/s}^2) \approx \frac{7.5}{\rho_b^{1.2}} \quad \text{for wooden items} \tag{6.7}$$

TABLE 6.7

HRR Parameters for Selected Items, Mean and Range

Item	Mass (kg)	HRR_{max} (kW)	a (kW/s²)	a_d (kW/s²)	t_{max} (s)
Chair with cushioning	9.8 (8.1–15.5)	362 ± 82	0.040 ± 0.03	0.0054 ± 0.0028	118 ± 94
Chair, rigid plastic	13.1 (10.8–17.7)	594 ± 131	0.019 ± 0.009	0.0029 ± 0.0013	83 ± 81
Single chair upholstered	19.9 (11.5–28.3)	1185 ± 56	0.11 ± 0.058	0.066 ± 0.0055	56 ± 48
Sofa, upholstered	25.5 (3.8–54.6)	1826 ± 676	0.12 ± 0.078	0.078 ± 0.018	46 ± 33
					THR (MJ)
Christmas trees (dry)	~5–10	800–1600	1–4	0.2–1.6	20–80
	~12–20	1600–5000	0.4–9	0.4–2.4	90–200

Source: Natori, A., *Fire Sci. Technol.*, 27(3), 310, 2008.

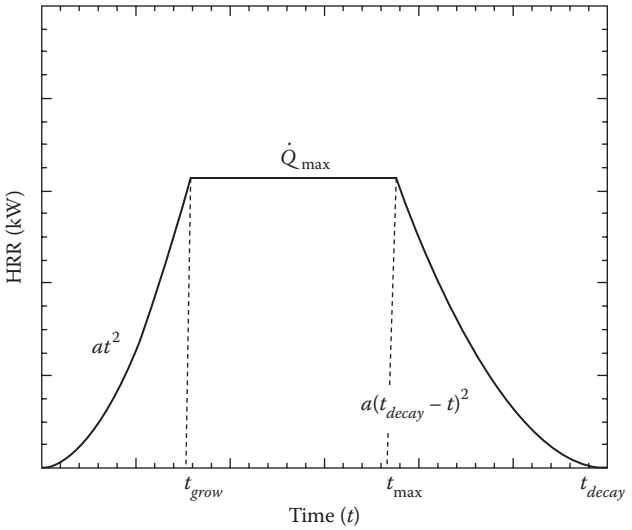

FIGURE 6.26
Natori firepower diagram. (From Natori, A., *Fire Sci. Technol.*, 27(3), 310, 2008.)

and

$$a\,(\mathrm{kW/s^2}) \approx \frac{0.15}{\rho_b^{0.5}} \quad \text{for plastic items} \tag{6.8}$$

The associated maximum HRR (firepower), $\mathrm{HRR_{max}}$, is given as

$$\mathrm{HRR_{max}} = (148 \pm 90\ \mathrm{kW/m^2})A_\mathrm{b}\ (\mathrm{m^2}) \quad \text{for wooden items} \tag{6.9}$$

and

$$\mathrm{HRR_{max}} = (272 \pm 204\ \mathrm{kW/m^2})A_\mathrm{b}\ (\mathrm{m^2}) \quad \text{for plastic items} \tag{6.10}$$

For estimations in HRR using Equations 6.7 through and 6.10, the portrayal of the fire growth curve would follow that of Figure 6.24 with no gradual t-squared decay. The duration of the fire is found by setting the area under the power–time curve equal to the THR based on the mass and heat of combustion of the item. For wood, recall the heat of combustion can range from about 11 to 15 kJ/g, while for a plastic, it can vary from 5 to 50 kJ/g.

Many other items can be categorized. The method of ignition and the incubation period before the t^2 rate ensues are important factors in determining the precise growth rate. The incubation period could be due to smoldering or simply the effect of a very slow initial spurious flame spread. Recently, I investigated a fire that began from a candle burning down in

a small glass cup holder filled with wax. This issue was the response of a smoke detector to the early fire growth. Another investigator hypothesized the fire growth as starting directly as a "medium" fire growth in the NFPA category of Figure 6.25. I considered the glass cup breaking and its wax burning before an adjacent item got involved. Experiments showed this is possible, and a surveillance video actually recorded such a start to fire in a closed restaurant bar. The growth rates for these two scenarios are very different.

6.8 Vehicle Fire Behavior

A very different type of growth rate compared to commodities and furnishing is that in an automobile. Figure 6.27 shows the rate of growth in a typical vintage sedan-type automobile passenger compartment of the 1990s due to a gasoline fire beneath, following collision damage. Yet in Figure 6.28, a post-collision fire originating in the engine compartment has a spurious growth for the various vehicles depicted. However, the shifted curves eliminating the incubation times show a remarkable similarity (with some typical variations)

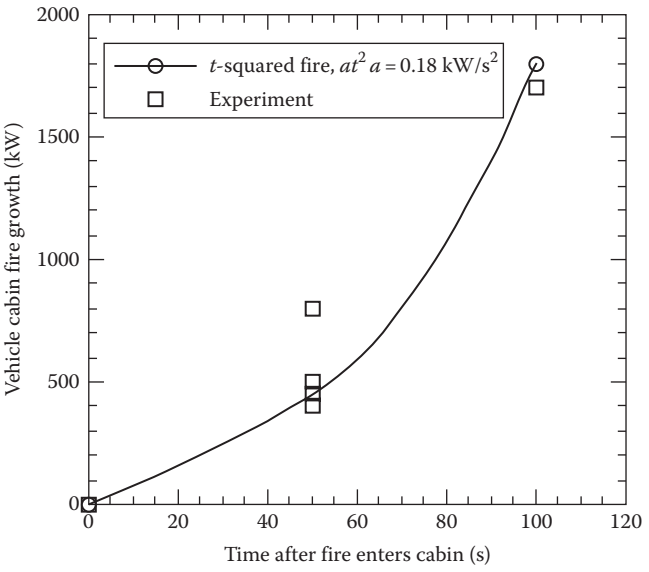

FIGURE 6.27
Fire growth in a vehicle passenger compartment due to gasoline spill following collision damage. (From Tewarson, A. et al., Comprehensive analysis of post collision motor vehicle fires, FM Global Technology Report 3018009, October 2004.)

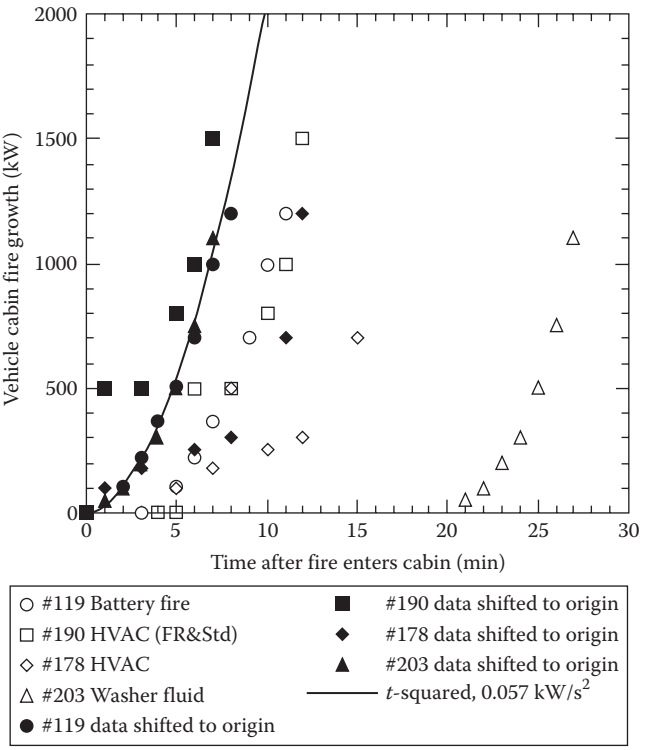

FIGURE 6.28
Growth rate in a passenger vehicle cabin from a fire coming from the engine, postcrash. (From Tewarson, A. et al., Comprehensive analysis of post collision motor vehicle fires, FM Global Technology Report 3018009, October 2004.)

as a t^2 fire growth in the passenger cabin.[14] Again, while a *t*-squared fit eliminating the incubation time appears reasonable, the incubation time is critical to a fire growth originating in the engine compartment and progressing into the cabin.

6.9 Extinction

Extinction of burning occurs if there is insufficient heat transfer to keep the gaseous fuel supplied, and the flame is cooled to a temperature that limits its survival. It shuts down. Recently, analysis of experiments in the burning of horizontal specimens has shown a tendency to extinguish at a critical (minimum) energy release flux (kW/m^2).[15] (Do not confuse this with heat flux. This is the energy release rate [HRR] per unit area of burning surface.)

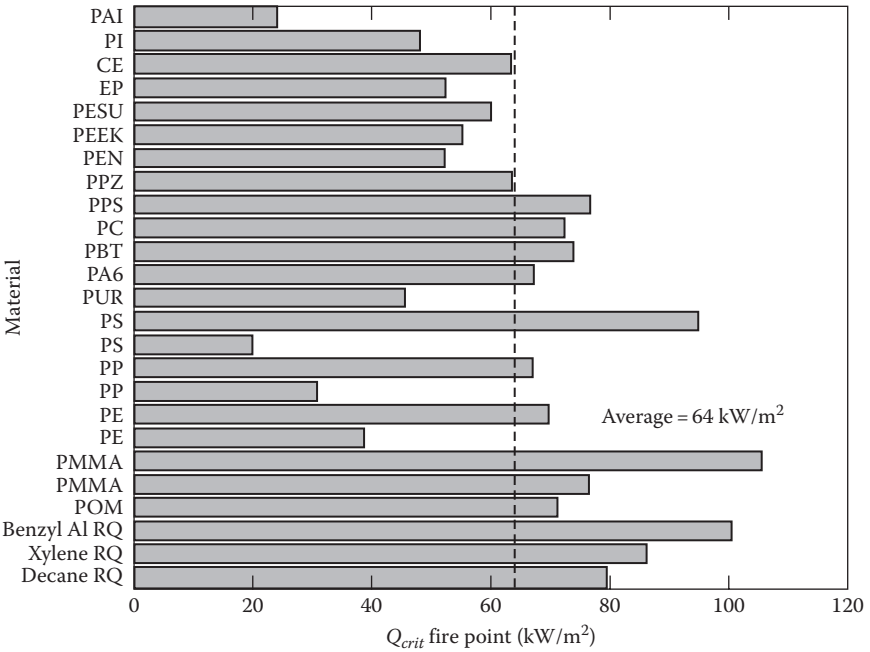

FIGURE 6.29
Minimum energy flux required for burning in the cone calorimeter. (From Lyon, R.E. and Quintiere, J.G., *Combust. Flame*, 151(4), December 2007.)

Figure 6.29 shows data taken for burning in air with natural convection (associated with a convective heat transfer coefficient of about 15 W/m^2-K) for polymers burning in the 10 × 10 cm configuration. While there is variation for the different materials, it is believed that most of the variation is inaccuracy caused by the inability to precisely measure the energy flux just before extinction. Unsteady burning and the lag time of scale response are responsible for such inaccuracies. It is readily seen that even for repeat results of the same polymer (PS, PP, PE, and PMMA), the variation is great. On average, the critical value is about 64 kW/m^2 with a standard deviation of about 22.

It can be shown from[15] that the critical energy flux for burning is dependent on the heat transfer coefficient and on the oxygen concentration. As a flame goes to extinction on a solid or liquid fuel, it becomes small and pure convection heat transfer from the flame might be expected. An approximate theoretical formula for the critical value of the energy flux when burning in air is

$$\dot{Q}''_{b,crit} \approx 5.4 h_c \text{ (W/m}^2\text{-K) in kW/m}^2 \tag{6.11}$$

The data shown in Figure 6.29 were taken in the cone calorimeter in which the heat transfer coefficient is about 12 W/m²-K. The computed critical value is 5.4(12) = 64.3 kW/m²… not bad! It should be recalled that earlier we indicated a critical mass flux at extinction of about 2 g/m²-s. Now we see this value depends on the heat of combustion. The heat of combustion corresponding to 2 g/m²-s would be 64.3/2 = 32.1 kJ/g.

6.10 Summary

After ignition a fire may grow over an area by flame spread. The burning rate (or fuel supply rate) can be determined for a material or item by knowing its mass burning flux ($\dot{m}''$), usually given in g/m²-s. Values less than 2 usually lead to extinguishment, and typical values range from 1 to 100 g/m²-s for surfaces, and higher for stacked commodities. The property called "heat of gasification" measures how much energy it takes to produce this gasified fuel; the property called "heat of combustion" gives how much energy is released when it burns. The ratio of these two properties, HRP, is a measure of the energy produced to energy required. The bigger it is, the greater the burning rate potential for a material.

A simple theory was presented to compute the mass burning flux from surfaces from its heat of gasification provided the flame heat flux is known. Despite some data for typical flame heat flux (see Chapter 3), a prediction of flame heat flux for a given fuel is beyond current science. However, much data exist on the maximum mass burning flux for fuels and for actual items burned. Energy release rate data, derived from large-scale calorimeters, provide a source for making estimates. A large amount of practical data has been expressed in terms of *t*-squared fires, and these data can provide a generic first estimate. The energy release rate (or alternatively, the burning rate) is the most significant factor in the indication of fire hazard. It relates to the potential for ignition of nearby items, to flashover potential in a room, and to the rate of water needed to extinguish the fire. The critical value of the energy flux at extinction for burning in air under natural convection is about 64 kW/m² and appears to be independent of fuel type on average.

Review Questions

1. Plexiglas, polymethyl methacrylate (PMMA), is often used as display windows and cases in art galleries and museums. If its flame imparts 30 kW/m² to the surface when it burns, estimate the energy release rate of a 2 m² square sheet (one side). You will need Tables 6.1 and 6.3, respectively.

2. Wood pallets 5 ft high and 6 × 6 ft in their plan dimension are ignited and burnt. Using Tables 6.5 and 6.6, respectively, estimate the following:
   a. Maximum energy release rate
   b. Time to reach 1 MW
   c. Its t^2 energy release rate curve
3. Graph the energy release rate of a generic sofa over time.
4. What is the peak energy release rate of a dry Christmas tree weighing about 7 kg?
5. A small wood stick match (2 mm diameter) flame has a heat transfer coefficient of 50 W/m^2-K. What is its energy flux when burning in air? Compare this to critical energy flux for burning.

True or False

1. All the gaseous fuel produced in a fully involved room fire burns in the room.
2. Weighing the object as it burns cannot determine its burning rate.
3. The heat of gasification and the heat of combustion are usually equal.
4. Fires on objects tend to grow proportional to time squared.
5. The heat flux from a turbulent flame, like its temperature, is nearly the same for all fuels.
6. Wood generally burns at a lower mass flux than plastics because it chars.
7. It is impossible to collect data for burning objects and make any sense out of it.
8. Objects burn at a higher rate in atmospheres of higher oxygen concentration as contemplated for space travel.
9. Water can work for extinguishment because it can lower the flame temperature and wet the surface.
10. Solid and liquid fuels can burn if their flame heat flux is high enough.

Activities

All fire experiments must be done with care in a safe place with protection and extinguishers available.

1. Obtain small shallow glass dishes ranging in size from 1 to 10 cm in diameter. Pour about 1/4 in. depth of a liquid fuel of high flashpoint (>25°C) into a dish. Ignite it and time its burning period. How does burning time vary with fuel diameter? Explain your results.

2. Obtain a collection of small wood sticks, roughly 4 × 1/4 × 1/4 in. Make a pile about 4 × 4 × 2 high, first putting all the sticks in contact, then leaving 1/4 in. spacing between the sticks in alternating layers. Try to ignite both with a match flame. Which pile burns? Why?
3. Examine the items contained in a room. From the data of this chapter, try to estimate the potential energy release rate of each item that could burn. Add to find their sum. Recognize that in a typical residential room, 1 MW could jeopardize it into flashover.
4. Do this with caution and safety glasses. Place a candle flame under a clear inverted glass bowl and observe extinction. Do not allow the flame to get near or touch the glass, and protect against cracking glass. Repeat this with a plant that remained in the inverted bowl overnight in an attempt to increase the oxygen.

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7

Fire Plumes

Learning Objectives

Upon completion of this chapter, you should be able to accomplish the following:

- Describe the meaning of buoyancy.
- Describe the behavior of fire plumes.
- Calculate flame height.
- Estimate temperature above a fire.

7.1 Introduction

All fires involve buoyancy, which sets the flow pattern and the nature of the flame. This flow pattern directs the growth of the fire and sucks in the air supply. It is also responsible for the characteristics of the smoke that departs the fire. Even under wind conditions, buoyancy plays a significant role in the fire's behavior. In this chapter, we consider in some detail the symmetric vertical fire that comes from the ignition of a release of gaseous fuel. When the fuel release is distributed on a horizontal surface (floor), this is commonly called a "pool" fire. It is representative of a liquid fuel spill or even the horizontal portion of cushion on a chair. Such fires are mostly turbulent, and the release of fuel gas at the surface is at a relatively low velocity. In a quiet atmosphere, the gases of the flame and hot smoke will rise vertically. This rising flow stream is called a "plume"—more specifically, a buoyant plume. However, in a wind, the plume will bend according to its

interaction with the wind, and eventually will follow the wind direction as the plume loses its buoyancy. Just what is buoyancy? And how do we differentiate between a flame due to fuel flowing at a high velocity and a flame that emerges from a burning liquid spill on a floor?

In this chapter, we shall examine the origin of buoyant flow, discriminate between jets and plumes, and develop an appreciation of how to compute the length of flames and their temperatures. For the most part, we shall consider fire plumes driven by natural convection alone. Equations will be developed in this chapter with the use of symbols to represent properties and flow features. The student having trouble with this should try to understand the process and not necessarily all the details. The main point is to focus on the result.

7.2 Buoyancy and Fluid Dynamics

The mixing of fuel gases and air to form a flame cannot be appreciated without some knowledge of fluid dynamics. The motion of a fluid (gas or liquid) is complex, and the equations that govern this flow are impossible to exactly solve. Computer models strive to do this and are further enlisted to solve the combustion that occurs in a flame. They are referred to as computational fluid dynamics (CFD) models. Any CFD model has approximations and cannot accurately represent all aspects of flows. Simplified models sometimes apply that can give us a first approximation to a complex fluid problem. Experimental data can be organized into general formulas that can apply over a wide range of problem variables. This latter process of equation development will be emphasized here. While the use of computers can be fun, the user may lack an understanding of what is happening. This is not good. In contrast, equation development requires an understanding of the fluid processes. The physics of the problem must be translated into mathematics. But often theory alone cannot complete the equation, and the strategic use of data can supply the ingredient to complete the process. This process will be illustrated.

The equations of fluid flow began with the work of Daniel Bernoulli in about 1733. He found that the kinetic energy (KE) of a fluid was nearly balanced by its potential energy (PE) due to gravity. However, there was a missing factor and that turned out to be *pressure*. You might say that Bernoulli discovered fluid pressure. Today, we know his relationship between velocity, gravity, and pressure as Bernoulli's equation:

$$\frac{\rho V^2}{2} + \rho g z + p = \text{constant along a streamline} \tag{7.1}$$

We now know that Bernoulli ignored the effects of friction in the fluid (or viscosity), and his equation only best applies away from surfaces. Here,

- ρ is the fluid density
- V is its velocity
- g is the symbol for the Earth's gravitational force per unit fluid mass, 9.81 N/kg
- z is the vertical height dimension
- p is pressure (force per unit area—all fluids exert this pressure equally in all directions)

The first term in Equation 7.1 is the KE per unit volume of fluid, and the second term is the PE per unit volume. The third term, pressure, could be considered as work done on the fluid (force × distance) per unit volume. Pressure supplies the work needed to push the fluid.

A streamline is the path; a particle attached to the fluid would follow in a steady flow in or around an object. A photograph of white streamlines in Figure 7.1 illustrates the flow over a cylinder. Notice the smooth orderly flow (*laminar*) at first is followed by the chaotic flow (*turbulent*) downstream. After a bit, all flows suffer from instability that leads to turbulence. Bernoulli's equation will hold provided fluid friction is not significant and will even hold along an average streamline in turbulent flow. Fluid friction is not so important away from surfaces, and Bernoulli will work very well there. This is a big approximation to the complex equations derived by Navier and Stokes in the early 1800s and now solved by CFD models today.

With this simple background of Bernoulli in fluid flow, jets and plumes can be examined as long as they are free of wall interference. A *jet* is a flow where the initial velocity is so large that it dominates the streamline pattern of the flow. A *plume* is a more quiet flow due to the motion of a light (or hot) fluid in a

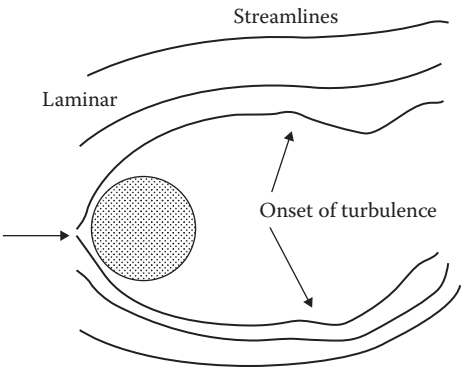

FIGURE 7.1
Streamlines in white for flow around a cylinder from an Album of Fluid Motion by van Dyke (1982).

heavier fluid (cold). This difference in density (or temperature) gives rise to an effective force called "buoyancy." A flow solely, or predominately, driven by its buoyancy, is called a "plume" if it is in a free atmosphere, not confined by walls.

A chimney flow has confined walls. But it is a bit easier to precisely describe the meaning and origin of buoyancy for the chimney flow. Let us apply Bernoulli's equation to a chimney flow and see how the buoyant force emerges. It will form the basis of plume flow.

Consider a vertical chimney with a horizontal intake at the bottom illustrated in Figure 7.2. Apply Equation 7.1 along the streamline from point 1 to 2. Then the values of the three terms, KE + PE + pressure work, are the same at 1 and 2. As the flow starts at rest in a big room, its KE or velocity is zero in the room at 1. If we take the datum for the elevation, z, at point 1, then z is zero there. So at point 1, we only have the pressure term. We label it p_1. At point 2, we have a velocity and an elevation giving PE. We also have a pressure that we label p_2 different in value from p_1. As this is a chimney, the temperature inside (T_H) is higher than the still air outside (T_C). From experience, we know hot air rises; we will now see why. Bernoulli's equation can explain this motion.

Apply Equation 7.1 between 1 and 2, recognizing that the constant in Equation 7.1 is the same at 1 and 2:

$$p_1 = \frac{\rho_H V_2^2}{2} + \rho_H g H + p_2 \tag{7.2}$$

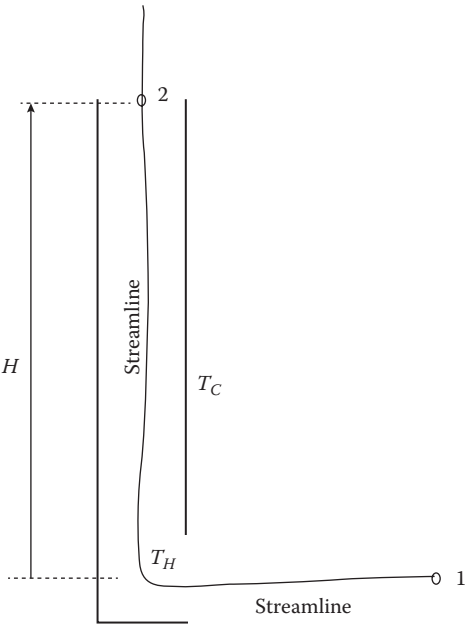

FIGURE 7.2
A streamline through a chimney.

The difference between the pressure at 1 and 2 *outside the chimney* is due to the weight of the cold, heavy, stationary air outside the chimney. The pressures at 1 and 2 are the same inside and outside the chimney, respectively. One can apply Equation 7.1 to the cold fluid at rest.

$$p_1 - p_2 = \rho_C g H \tag{7.3}$$

Combining Equations 7.2 and 7.3 to eliminate the pressures gives a result for the motion of hot gases out of the chimney:

$$\frac{\rho_H V_2^2}{2} = (\rho_C - \rho_H) g H \tag{7.4}$$

The term on the right-hand side is the *buoyant force per unit volume*. It could be interpreted as the PE difference between the cold and hot air. This is buoyancy. The difference in density has given rise to the velocity (V_2) out of the chimney.

An alternative means to express this answer for the outflow is to put it in terms of temperatures instead of densities. If this chimney is at sea level, the atmospheric pressure is 101.325 kPa (kilopascal) (or 14.696 psi), and at 20°C, the density is 1.20 kg/m^3. Then the pressure difference between 1 and 2 from Equation 7.4 would be

$$p_1 - p_2 = \rho_C g H = 1.20 \text{ kg/m}^3 \times 9.81 \text{ N/kg} \times H \text{ (m)}$$

For H = 1 m, this is about 11.8 Pa (1 N/m^2 = 1 Pa). Even if H is 1000 m, the pressure difference is still about 1/10th of the total atmospheric pressure (11.8 kPa compared to 101 kPa). Therefore, the pressure difference over practical heights in the Earth's atmosphere is small. So the pressure throughout the height might be considered almost constant. This is the case for fire flows in general, even throughout a tall building.

However, while pressure overall will be nearly constant, differences in pressure will arise due to buoyancy. More appropriately for fire-induced flows, these differences are better described in terms of temperature. For example, hot smoke properties can be related to cold smoke (mostly nitrogen for air and combustion products) by a relationship that requires $\rho_C T_C = \rho_H T_H$. (In general, this is called an "equation of state.") From this result, Equation 7.4 can be rearranged as

$$\frac{V_2^2}{((T_H - T_C)/T_C) g H} = 2 \tag{7.5}$$

The term in the denominator represents the buoyancy effect. The quantity on the left-hand side of Equation 7.5 has no dimensions since it is equal to a number 2. It is a "dimensionless number," and it has the name Froude (Fr) number. Physically, it can be considered as the ratio of momentum to buoyant force. It is seen in this case for the chimney that Fr = 2.

Removing the walls from this chimney example can then be considered as an approximation to a vertical plume. For vertical turbulent plumes, in a static atmosphere, with and without flames, this Froude number is found to be a constant of about 1.5 ± 0.1 at all heights.[1] Recall that Bernoulli's equation holds for ideal frictionless flow and real plumes dissipate some energy by friction. This can explain the difference between 1.5 and ideally 2. Still the result of 1.5 compared to 2 suggests very little is lost due to friction in a buoyant plume. Momentum appears to lose about 25% (2–1.5)/2, to friction at any location. So for a turbulent fire plume Equation 7.5 applies with a constant of 1.5.

7.3 Turbulent Fire Plumes and Jets

Let us just consider here just turbulent conditions, as laminar flames are very small and their plume quickly becomes turbulent above the flame. A *fire plume* is the buoyant column of flame and hot combustion products rising above the fuel source. *Buoyancy* is the force that arises due to density differences. Because density is inversely proportional to temperature for gases, plume temperatures cause an upward force on the hot gases relative to the surrounding air (see Figure 7.3). If the hot plume gases cool to the local air

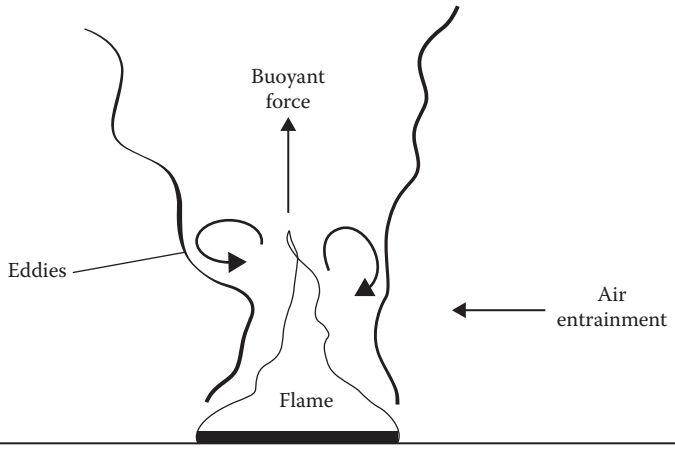

FIGURE 7.3
Buoyancy and fire plumes.

temperature, the buoyant force would become zero, causing the plume to cease rising. This condition is responsible for cigarette smoke stratifying in a room with a common slight rise in temperature as it moves up. Also the plume from a forest fire will eventually even out in the atmosphere, and move only horizontally with the wind, as do clouds of water vapor. If buoyancy is the only force responsible for the motion of the plume, we expect its Froude number to be about 1.5. However, the character of the flow is very different if the initial velocity of the hot gases or the initial velocity of the fuel is large. Such a flow can arise from a high-pressure tank. In this case, the initial "jet" velocity controls the flow, not the buoyancy. In quantitative terms, this will occur if the initial Froude number is greater than 1.5. A jet can be distinguished from a hot plume by how far it will travel horizontally before rising due to its buoyancy. The greater the horizontal distance, the stronger is the jet.

7.4 Buoyant Plumes

As the hot gases rise in a buoyant plume, the colder air is induced to flow into the fire plume. This flow process is called "entrainment" (see Figure 7.3). In fact, all flows in a free atmosphere at rest will entrain the surrounding flow. This occurs for two reasons. In purely laminar flows, the fluid friction drags the neighboring fluid along, and it becomes part of the jet or plume as it continues. The rate of this entrainment flow is responsible for the flame height and the characteristics of the fire plume. Consequently, the fire is intertwined with the airflow, each depending on the other.

In general, flow can be laminar or turbulent. Laminar flow is smooth and orderly. The candle flame is laminar, but its buoyant plume of heated gases becomes turbulent at roughly 1 ft (or less) above the flame. This characteristic can be seen by directing a collimated beam of light through the candle flame and its plume and projecting the resultant image on a screen. The fluctuating light and dark images of the plume illustrate high-frequency turbulence. Within a turbulent flame, this high-frequency motion of the reaction zone can produce oscillations of hundreds of degrees at a fixed point. Superimposed on these high-frequency fluctuations, as high as 10 cycles per second (10 Hertz [Hz]), are large-scale fluctuations as a direct result of buoyancy and fluid friction. As the buoyancy causes the plume fluid to rise, its cooler edges are slowed and fall back down. This results in recirculating regions or *eddies* comparable in size to the fuel diameter, as illustrated in Figure 7.4. These eddies rotate as well as rise along the edges of the plume. They undoubtedly influence entrainment.

The large eddy turbulent effects present in all buoyant plumes can have a profound effect on flame height in combusting plumes. Although these

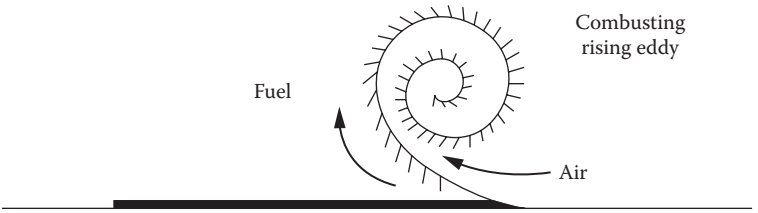

FIGURE 7.4
Turbulent burning eddy.

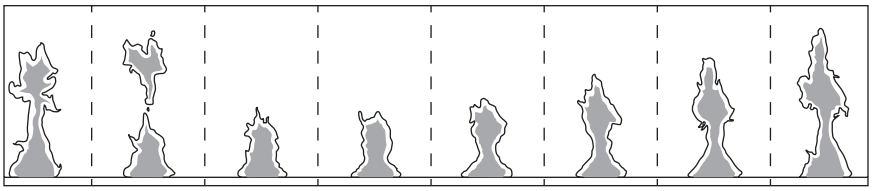

FIGURE 7.5
A sequence of flame images over a 0.3 second period for a 0.3 m diameter fire. (After McCaffrey, B.J., Purely buoyant diffusion flames: Some experimental results, NBSIR 79-1910, National Bureau of Standards, Gaithersburg, MD, 1979.)

turbulent flames are diffusion flames, the diffusion mechanism of bringing the fuel and oxygen together by concentration differences alone is now embedded within the turbulent flow. The outer eddies produce a rising *vortex* between them. The high-frequency turbulence distorts this image, as illustrated in Figure 7.5. As this burning eddy rises, it extends the flame until the fuel burns out. A new eddy then carries the flame to this former height. As a result, the flame height can fluctuate over a significant distance. Figure 7.5 shows that the maximum height can be roughly twice its minimum. Although these sketches are shown for flames of a 0.3 m diameter burner with an eddy frequency of 3 Hz, this difference in heights is typical of buoyant turbulent flames. When we address flame height and plume temperatures, we should keep in mind that the flame is unsteady, undergoing high frequency as well as slower eddy fluctuations. Formulas for flame height usually only give average results and do not account for the periodic "ripping off" of the flame shown in Figure 7.5.

The frequency of formation and departure of the outer eddies from the base of the plume (called vortex shedding) depends on the base diameter of the fire, D. This vortex shedding frequency in Hertz for a fire of diameter D in meters is approximately

$$f = \frac{1.5}{\sqrt{D}} \tag{7.6}$$

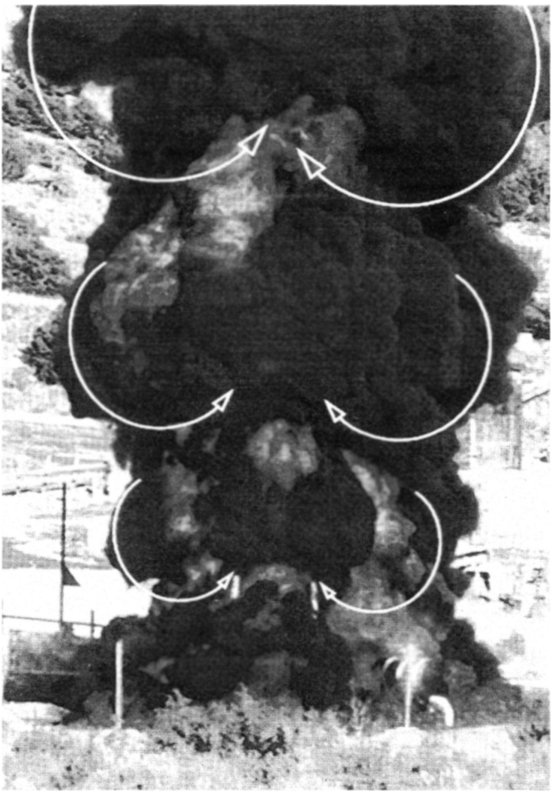

FIGURE 7.6
Photograph of a 10 m diameter liquid fire. (Courtesy of L.A. Gritzo, Sandia National Laboratories, Albuquerque, NM.)

A 10 cm fire would shed eddies about five times per second, but a large wildland fire of 100 m would form a vortex every 10 seconds. Figure 7.6 shows a photograph of a large liquid fuel fire (approximately 10 m diameter) that illustrates the eddies. Note that the eddies are of size comparable to the diameter, whereas the high-frequency turbulence has much finer length scales. This photograph also illustrates the engulfment of the flame by black soot carried by these eddies to the colder fringes of the flame where the soot does not burn.

7.5 Flame Height

Here, we restrict our attention to symmetrical fires from circular horizontal fuel sources. These are called "pool fires," representative of liquid fuel spills. However, the results can approximate other symmetric fuel shapes burning

on a floor. We will discuss this later. *Line fires* and wall fires have somewhat different quantitative characteristics but are qualitatively similar in behavior of pool fires. We also will address principally turbulent fires, with no wind effects, dominated by buoyant effects. However, let us first consider a range of conditions to give a quantitative perspective.

7.5.1 Jet Flames

Consider gaseous fuel issuing from a pipe of diameter D at an exit velocity V_e. For a given fuel and a fixed pipe diameter, the ignited gases will result in an increasing laminar flame as V_e is increased, as shown in Figure 7.7. As the exit velocity is increased, the flame is maintained as laminar up to a maximum length of nearly a distance of 200 diameters. At higher velocities, the flow becomes turbulent and the flame length becomes fixed for a given fuel and pipe diameter. This phenomenon of a fixed turbulent flame height is a direct result of the entrainment process. The basis for the prediction of flame length is that the visible flame ends when all of the fuel is burned. Because the fuel is supplied at the base, the end of the combustion process is controlled by how fast the air is entrained over the length of the fire plume. This entrainment process is illustrated in Figure 7.8. The chemical reaction rate is fast compared to how fast air is supplied to meet the fuel

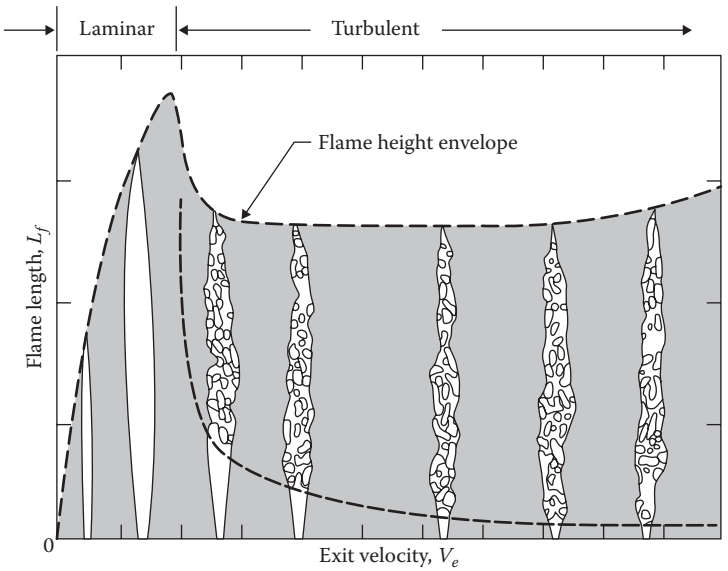

FIGURE 7.7
Flame lengths for gaseous jets issuing from a pipe of fixed diameter. (From Hottel, H.C. and Hawthorne, W.R., Diffusion in laminar flame jets, in: *Third Symposium on Combustion and Flames and Explosion Phenomena*, Williams & Wilkins, Baltimore, MD, 1949, pp. 254–266.)

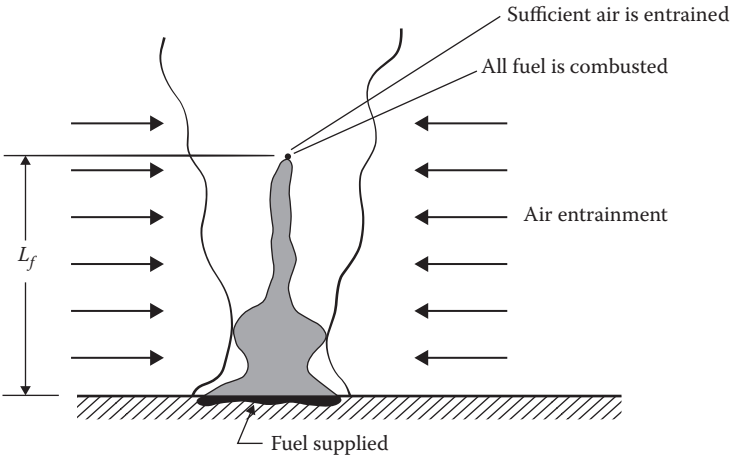

FIGURE 7.8
Air entrainment and flame length.

so the fuel reacts almost immediately when it encounters air. This is why the entrainment of air controls the combustion process, and therefore the height of the flame.

Let us examine the turbulent fuel jet of Figure 7.7. The fuel supplied must completely react by the end of the flame and combine with the air entrained. Let us see if we can explain why the flame stays at a fixed length. The rate of air supplied (by mass) is equal to air density (ρ_a) times entrainment velocity (V_e) times the area through which the air was entrained. This area can be approximated as πDL_f since the jet does not expand by much. Then proportionally, we represent

$$\text{Rate of air mass entrained} = \rho_a \pi D L_f V_e \tag{7.7}$$

where

ρ_a is the density of the surrounding air
D is the pipe exit flow diameter
L_f is the flame length

The mass rate of fuel supplied through the pipe is the density of the fuel (ρ_f) times the velocity of the fuel supplied (V_f) times the area of the pipe exit ($\pi D^2/4$). In symbols, this is

$$\dot{m}_f = \frac{\pi}{4} \rho_f V_f D^2 \tag{7.8}$$

These two mass flow rates must be at least in *stoichiometric* proportion in order for the air to burn all of the fuel. Usually, for turbulent conditions, this process may not be so efficient and it requires more air than needed for stoichiometric combustion. Turbulence controls the excess air, and this is not a function of the fuel type. We will have more air than needed; the process is said to be "fuel lean." Stoichiometric here implies that the *stoichiometric air-to-fuel mass ratio* (s) is that determined for a complete chemical reaction.

Before relating these two mass flows by their stoichiometric ratio, we need one more element. The jet velocity controls the entrainment velocity into the jet, where the fuel and air mix. This is a result that holds up from measurements in the turbulent flow of jets and plumes. As a consequence, the entrainment velocity is found to be about 1/10th of the jet velocity. For the jet, as the pipe exit velocity controls the flow in the combustion region, we take the jet velocity to be the fuel velocity at the exit. Therefore, from Equations 7.7 and 7.8, by replacing the fuel velocity with the entrainment velocity, we have the following proportionality:

$$\frac{\rho_a D L_f V_e}{\rho_f (\pi/4) D^2 V_e} \propto s$$

or solving,

$$\frac{L_f}{D} \sim \frac{(\rho_f) s}{\rho_a} \tag{7.9}$$

This result explains why the turbulent jet flame length becomes constant for a given fuel (having density ρ_f and stoichiometric ratio s) at a given diameter. Such turbulent jet flames commence at exit velocities much higher than those due to purely buoyancy-induced flame velocities. Jet flames would be relevant for ruptures of high-pressure gas lines. We now examine more closely purely buoyant flames.

7.5.2 Pool Fire Flames

If we examine the "exit" velocity of fuel gases leaving the vaporizing solid or liquid fuel as they burn in still air, we would find these velocities are very low, not in the range to be considered jet velocities. For example, in Chapter 6, we saw that the maximum burning mass flux for a gasoline pool fire is 55 g/m^2-s. Because the vaporized gasoline is about twice as dense as air, the velocity of these vapors would be approximately

$$V_e \approx \frac{55\ \text{g/m}^2\text{-s}}{2000\ \text{g/m}^3} \approx 3\ \text{cm/s}$$

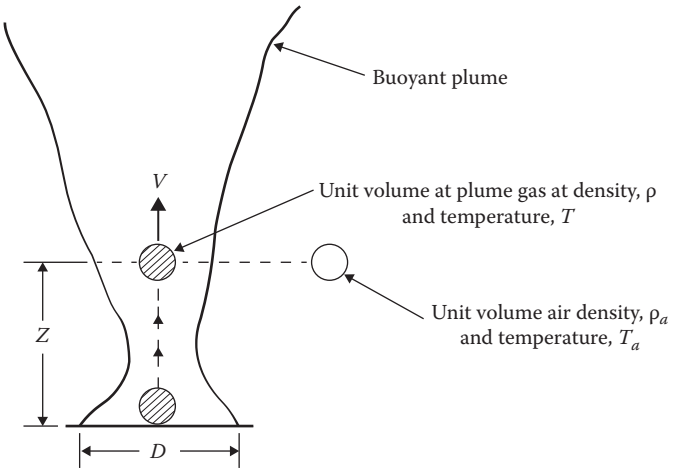

FIGURE 7.9
Exchange of buoyant potential energy into kinetic energy of the fire plume.

This velocity is not responsible for the subsequent entrainment of air. That entrainment results from the substantial increase in fire plume velocities due to combustion and its resulting buoyancy.

Let us estimate this buoyant flow velocity. A simple explanation for this velocity is that the relative buoyant PE is converted into KE. For a unit volume of gas in the fire plume, Figure 7.9 illustrates this energy transfer. We reason that the relative PE per unit volume at height z under the gravitational acceleration g is

$$(\rho_a - \rho)gz$$

and the KE per unit volume (considering negligible starting KE) is

$$\rho\frac{V^2}{2}$$

Equating these energies gives the plume velocity as

$$V = \sqrt{\frac{2(\rho_a - \rho)gz}{\rho}}$$

or in terms of temperatures,

$$V = \sqrt{\frac{2(T - T_a)gz}{T_a}} \tag{7.10}$$

where $T/T_a = \rho_a/\rho$, that is, the temperature is inversely dependent on density. Because the gravitational acceleration, g, is 9.81 m/s^2, this velocity is approximately 4.5 m/s for z = 1 m and $(T - T_a)/T_a = 1$. So, for our gasoline fire example with a flame height of say 1 m, the fire plume velocity is more than 100 times the vaporization velocity (i.e., 3 cm/s). This fire plume velocity controls the entrainment of air into the fire. By a process similar to that leading to Equation 7.9, we can obtain a formula for the height of this buoyant flame. We shall arrive at a formula that will illustrate the nature of the factors that control flame height for a fire plume. Unlike the jet where the exiting fuel velocity controls entrainment, here the plume velocity controls. So in Equation 7.4, V_e is proportional to V of Equation 7.10. The fuel mass flow rate ($\dot{m}_f$) times the stoichiometric ratio of air to fuel is related to the mass flow rate of air entrained up to the end of the flame. Writing this as a proportionality:

$$\frac{\rho_a D L_f V_e}{\dot{m}_f} \propto s$$

we can now solve for the flame height. But first recognize from Equation 7.10 that the maximum plume velocity and therefore the entrainment velocity is proportional to $\sqrt{gL_f}$ where L_f denotes the flame length, z. This assumes the flame temperature is constant, and we shall prove this shortly. Now substituting and rearranging, we find that the ratio of flame height to fire base diameter is proportional to

$$\frac{L_f}{D} \propto \left(\frac{\dot{m}_f s}{\rho_a \sqrt{gD} D^2} \right)^{2/3}$$

We can stop here, but it is useful to introduce the ratio of combustion energy per unit mass (the heat of combustion, ΔH_c) to the thermal energy per unit mass of air ($c_{pa}T_a$). Then we get

$$\frac{L_f}{D} \propto \left(\frac{\dot{m}_f \Delta H_c}{\rho_a c_{pa} T_a \sqrt{gD} D^2} \right)^{2/3} \left(\frac{s c_{pa} T_a}{\Delta H_c} \right)^{2/3}$$

The second quantity $sc_{pa}T_a/\Delta H_c$ is a constant as the specific heat of air and its temperature is fixed, and $\Delta H_c/s$ is the heat of combustion per unit mass of air, a near constant of about 2.9–3.0 kJ/g for most hydrocarbons. The first quantity is a very important factor that shows up in many fire formulas. It represents the combustion energy release rate (HHR or $\dot{Q}$) to the thermal flow energy of the air. It is given the symbol Q^* as first introduced by Professor Edward Zukoski of the California Institute of Technology. Ed was

a pioneer of fire science and contributed to many aspects of fire research including flame height, plume entrainment, and compartment fires. He often showed the presence of Q^* in formulas related to these phenomena. Many now call Q^* the Zukoski number.

This quantity Q^* is a *dimensionless* property of the turbulent fire and is computed as

$$Q^* = \frac{\dot{Q}}{\rho_a c_{pa} T_a \sqrt{gD} D^2} \tag{7.11}$$

where

ρ_a is the air density (1.2 kg/m^3)
c_{pa} is the air specific heat (1.0 kJ/kg-K)
T_a is the air temperature (usually at 20°C or 293 K)
$\dot{Q}$ is the energy release rate of the fire (kW)
D is the pool diameter (m)
g is the gravitational acceleration (9.81 m/s^2)

In these units

$$Q^* = \frac{\dot{Q}\,(\text{kW})}{1101[D\,(\text{m})]^{5/2}} \tag{7.12}$$

Our 1 m diameter, gasoline fire of Chapter 6 where $\dot{Q}$ = 1887 kW has a Q^* of 1.7. Typical natural fires may range from Q^* values of 0.5 to 100 for very large diameter fires to stacked wooden pallets, respectively.

While Q^* is the ratio of combustion energy to a nominal flow energy of the plume, it can also be interpreted as a length ratio. By taking it to the 2/5th power:

$$(Q^*)^{2/5} = \frac{(\dot{Q}/\rho_a c_{pa} T_a \sqrt{g})^{2/5}}{D} \tag{7.13}$$

The numerator now has dimensions of length. This numerator represents a *characteristic combustion length* of the fire and is directly related to the flame length. It also can be characteristic of the size of the large vortices associated with buoyant plumes.

Measurements of flame height by various investigators have all shown that the flame length is related to Q^*. Figure 7.10 shows a range of experimental results that illustrates the full spectrum from low Q^* buoyant plume fires (conflagrations) to jet flames where buoyancy is unimportant (~Q^* = 10^6). An approximate demarcation between purely buoyant pool fire behavior and where jet flames commence is approximately $Q^* \sim 10^4$. Over a range of most

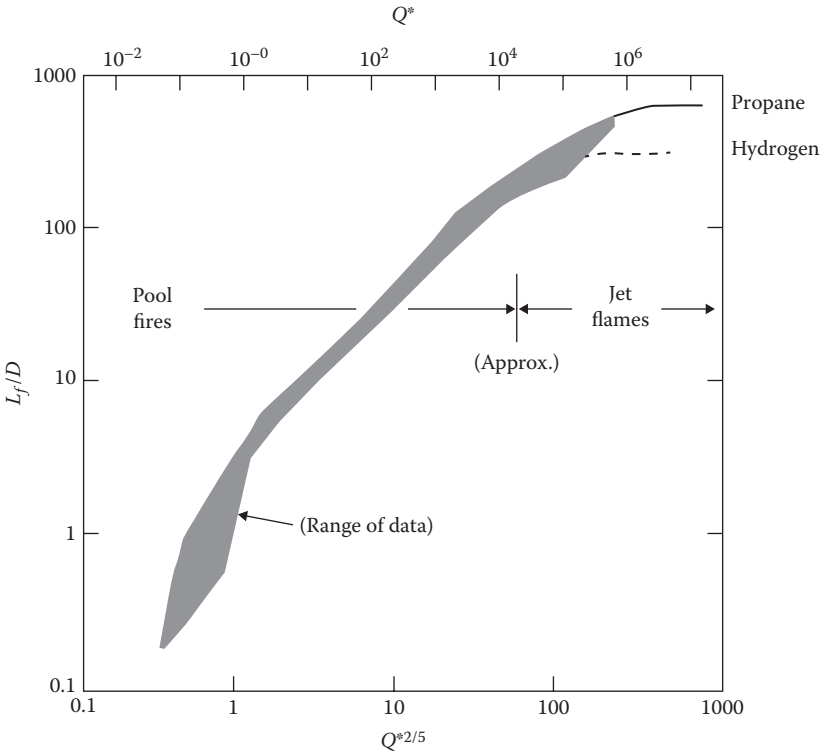

FIGURE 7.10
Flame length for a range of symmetric fire conditions in terms of Q^*. (After McCaffrey, B.J., Flame height, Chap. 2-1, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June, 1995.)

natural fires, $0.5 \leq Q^* < 100$, a relatively simple formula (from Heskestad[4]) gives a good estimate of the average flame height.

$$L_f = 0.23\dot{Q}^{2/5} - 1.02D \tag{7.14}$$

where
$\dot{Q}$ is in kilowatts
L_f and D are in meters

Recall that the flame height may fluctuate in time by a factor of 2 from its minimum to its maximum height, as depicted in Figure 7.5, so Equation 7.14 represents an average flame height. The most uncertainty exists below Q^* of 0.5. We shall see from the next section that Equation 7.14 favors the maximum flame height. As the flame fluctuates, there is a region where combustion

always occurs (a continuous flame region), and above it there is an intermittent region where flames reach their maximum.

Let us investigate the temperatures in this intermittent flame and in the above noncombusting plume.

7.6 Fire Plume Temperatures

The temperatures within a turbulent fire plume vary across the width of the plume from a maximum at the center to the air temperature at the edge. We shall consider the centerline maximum temperature along the height (z) of a turbulent buoyant fire plume. The variation with height depends on whether z is within the combustion zone ($z \leq L_f$) or the noncombusting zone ($z > L_f$). We can consider a simple theory to explain these vertical temperature variations. Over the combusting region, the flame generates $\dot{Q}$ energy release rate and radiates a fraction (X_r) of this energy away from the flame to the surroundings. The energy that stays in the flame at the end of the combustion region at $z = L_f$ is $(1 - X_r)\dot{Q}$. The energy release rate is distributed over the flame length as the entrained air reacts with the fuel present. Once all the fuel is reacted at $z = L_f$, the energy rate $(1 - X_r)\dot{Q}$ remains constant after that throughout the noncombusting plume region. These processes are illustrated in Figure 7.11. Let us see if our background of fire plumes can give us some information on how the temperature will behave.

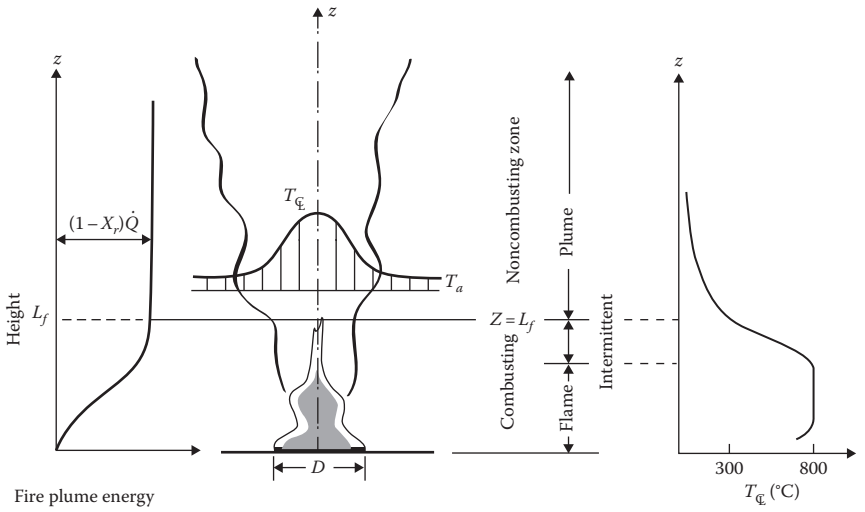

FIGURE 7.11
Fire plume energetics.

7.6.1 Analyses to Predict the Plume Temperature

Consider the combustion zone where $z \leq L_f$. The energy by combustion that stays in the fire plume by conservation of energy must equal the thermal flow energy of the plume. The flow energy rate of the plume is represented by the mass flow rate times the thermal energy of the plume. In symbols, this is

$$\dot{Q} = \dot{m} c_p (T - T_a) \text{ (kW)} \tag{7.15}$$

where
c_p is the specific heat of the plume gases
$\dot{m}$ is the mass flow rate of the plume gases

The mass flow rate in the plume is nearly equal to the air entrainment rate, as the amount of fuel supplied is relatively small. We can write, in detail, the energy released due to the combustion process as

$$\dot{Q} = \dot{m}_f \Delta H_c (1 - X_r) \text{ (kW)} \tag{7.16}$$

where
$\dot{m}_f$ is the mass rate of fuel reacted up to height, z, g/s;
ΔH_c is the heat of combustion, (kJ/g)

It has been stated that more air than stoichiometrically required is entrained over the flame. In other words, the turbulent mixing does not allow the available fuel to readily react with the entrained air. Let us say n-times stoichiometric air is entrained and is needed to complete this fuel-lean combustion. We can therefore write that the mass air entrainment rate is

$$\dot{m} = ns\dot{m}_f \tag{7.17}$$

where
s is the stoichiometric mass air-to-fuel ratio
n is the multiple of stoichiometric air required due to inefficient mixing

By equating Equations 7.15 and 7.16 and substituting Equation 7.17, it follows that the temperature rise in the fire plume is

$$T - T_a = \frac{\Delta H_c (1 - X_r)}{c_p ns} \tag{7.18}$$

$\Delta H_c/s$ is approximately constant (2.9 kJ/g air) for most all hydrocarbon fuels, $c_p \approx 10^{-3}$ kJ/g-K for air, and it is experimentally found that n is

approximately 9.6.[1] The average turbulent flame temperature rise along the centerline of a fire plume is approximately (for air initially at 20°C)

$$T - T_a \approx 1450(1 - X_r)\ (°C) \tag{7.19}$$

This result demonstrates that the temperature within the combusting zone is not dependent on fuel type except for variations in X_r. We saw that X_r can range from 0.15 to 0.60 for different fuels and may also depend on the scale of the pool fire (Figure 3.10 and Tables 3.3 and 3.4). Large pool fires or very sooty fuels may have the tendency to shroud the luminous flame in cooler black soot as seen in Figure 7.6. This shroud of soot can block the outgoing flame radiation, making X_r smaller and T larger. This result has been found for large pool fires and indicates a maximum possible fire plume turbulent temperature of nearly 1500°C.

How about the temperature along the plume centerline as we move above the flame. Continued entrainment of air will drop the temperature. It is not surprising that this temperature rise depends on Q^*. But here Q^* is based on the dimension z, the height along the plume, rather than the base diameter. Although there is a small effect of the base diameter, we will ignore it here. We represent this behavior as

$$\frac{T - T_a}{T_a} \sim \text{function}\,\frac{z}{(\dot{Q} / \rho_a c_{pa} T_a \sqrt{g})^{2/5}} \tag{7.20}$$

for a wide range of pool fire data.

Figure 7.12 represents this correlation shown for methane fires of 15 kW to 60 kW. Although the data are scattered to some degree, the line represents the correlation distinctly in three regions: (1) combusting, (2) intermittent, and (3) noncombusting plume. The end of the intermittent zone—the maximum flame tip—is at $z/\dot{Q}^{2/5} = 0.20\ \text{m/kW}^{2/5}$, which is consistent with the coefficient 0.23 of Equation 7.14. The correlation shows a maximum (time-averaged) turbulent flame temperature of approximately 800°C for these data in which X_r was about 0.3. Applying Equation 7.19 would give a centerline temperature rise in the combustion zone of 1015°C. Actually, this is more correct than the data in Figure 7.12 because the thermocouples used to measure the fire temperatures were not corrected for their radiation loss. So by losing heat, they read too low. As the temperature drops, the data are more accurate. It should be noted that the centerline temperature of slightly over 300°C occurs at the tip of the flame. Heskestad[4] commonly associated a temperature rise of 500°C as his measure of the average flame height. Importantly, turbulent flame plumes have a similarity in that, despite the value of the flame height, the fire plume's temperature rise at the flame's maximum tip at the end of the intermittent zone can always be taken as about 300°C.

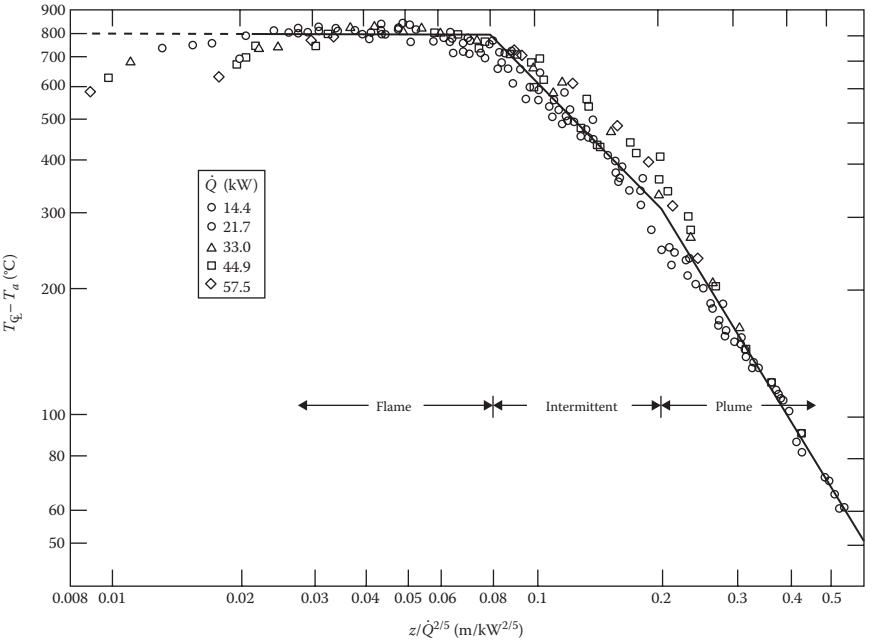

FIGURE 7.12
Centerline fire plume temperatures. (After McCaffrey, B.J., Purely buoyant diffusion flames: Some experimental results, NBSIR 79-1910, National Bureau of Standards, Gaithersburg, MD, 1979.)

Although Figure 7.12 only contains data from one fuel (methane), other experimental results for hydrocarbon fuels have shown the approximate universality of the graph. However, as the pool fire diameter increases, sooting can reduce X_r, causing maximum centerline turbulent flame temperatures as high as 1200°C or more. Except for this higher plateau in the flame region of Figure 7.12 as the fire gets larger in diameter, the rest of the correlation still applies. More important, for hydrocarbon fuels, the turbulent flame temperature is independent of fuel and can generally be taken as approximately 800°C for moderate fire sizes. Again, this 800°C rise is not corrected for radiation error, and more accurately it is more like 1000°C. But commonly thermocouple data are not corrected in fire experiments.

Gasoline and wood fires should show no temperature differences at the flame tip, but their flames lengths may be significantly different. These flames have a similarity. They can be stretched and squeezed, but their temperature distributions are the same relative to the combusting and noncombusting zones.

7.6.2 Flame Height and Temperature Calculations

Compute the average flame height, and the centerline fire plume temperature at this flame height for four fuels, 1 m in diameter. These fires were

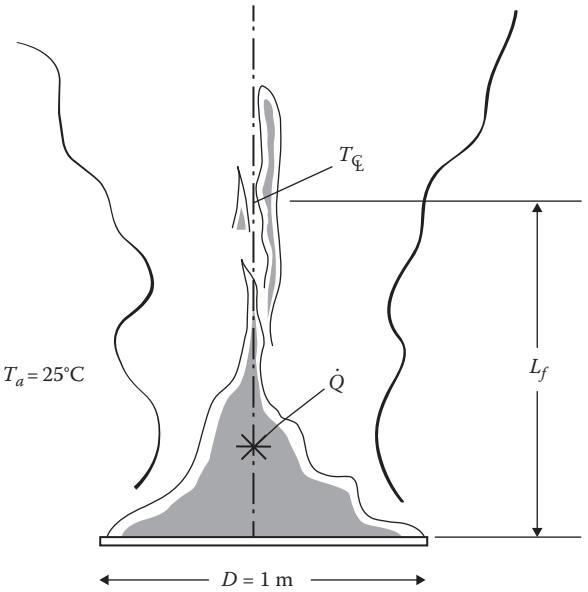

FIGURE 7.13
Example computing the average flame height and temperature at that location.

previously used in Chapter 6. The four fuels are wood, polystyrene, heptane, and gasoline. See Figure 7.13 as an illustration of the example.

Using Equation 7.14,

$$L_f = 0.23\dot{Q}^{2/5} - 1.02D$$

where $\dot{Q}$ is in kilowatts, and D = 1 m. Use the values of $\dot{Q}$ computed in Chapter 6. The flame height results follow:

Wood:

$$L_f = 0.23(130 \text{ kW})^{2/5} - 1.02(1 \text{ m}) = 0.59 \text{ m}$$

Polystyrene:

$$L_f = 0.23(1189 \text{ kW})^{2/5} - 1.02(1 \text{ m}) = 2.89 \text{ m}$$

Heptane:

$$L_f = 0.23(2661 \text{ kW})^{2/5} - 1.02(1 \text{ m}) = 4.37 \text{ m}$$

Gasoline:

$$L_f = 0.23(1887 \text{ kW})^{2/5} - 1.02(1 \text{ m}) = 3.68 \text{ m}$$

The temperature is found from Figure 7.12. Although flame radiation varies for the fuels, the graph does not account for the effect of X_r. This is not perfectly correct, but we do not have better results to work with here. More sophisticated analyses would not change our results from the graph. So let us proceed. The following fire plume temperatures at $z = L_f$ on the centerline are obtained by computing the horizontal axis of the graph and obtaining the temperature rise from the vertical axis.

Fuel	T(°C)
Wood	740
Polystyrene	400
Heptane	330
Gasoline	340

The wood result is indicative of a temperature in the continuous flame region, while the others are indicative of the peak flame height. The wood result is not correct. Recall that the wood here is a wood crib that has some height to it. Indeed, Heskestad[5] has shown that Equation 7.14 holds for arrays of commodities as well as pool (flat-based) fires. His arrays were stacked wood pallets 0.3–3.4 m high and rack storage commodities of 3–6 m high. The equation applies provided the flame height is measured from the base of the array, and the diameter has an effective value taken as $D = (4\dot{Q}/\pi\dot{Q}'')^{1/2}$. The energy flux for the array can be taken from Table 6.5. If the wood were represented as a crib with some height to it, say 1.3 ft, by Table 6.5 this wood pallet stack (crib) would have a firepower of 1021 kW for a 1 m diameter. This firepower is more than that estimated for the wood by using Table 6.2. The value in Table 6.2 must depend on the height of the crib and cannot be general. With this adjustment for the wood, the temperature rise is more like 400°C. Recall that no effect of the radiation fraction was taken into account, and that the temperatures of Figure 7.12 were not corrected. Roughly, the results indicate that the temperature rise at the flame height was always about the same, 330°C–400°C, with some inconsistency due to using a formula for flame height with a general correlation for fire temperature. In principle, the temperatures should be the same at the flame with some variation due to differences in radiation fraction of the fuel.

7.6.3 Nature of Turbulent Flame Temperature

We have just seen that the turbulent flame temperature rise for moderate size pool fires (and it could be shown for other fire configurations) is nearly a constant maximum of approximately 800°C and independent of fuel, particularly hydrocarbons. Literature values of *adiabatic flame temperatures* for hydrocarbon fuels burning in air typically range from 2000°C to

2300°C with measured laminar flame temperature of 1800°C–2000°C. Why are turbulent fires 800°C or 1200°C at most? To understand this, we must understand what is being measured and therefore sensed by a thermometer or thermocouple.

The *adiabatic flame temperature* is the maximum possible temperature that can be achieved for that particular combustion process of a fuel. Adiabatic means perfectly insulated; there is no heat loss from the reaction zone. As shown in Chapter 2, the candle flame is representative of a laminar diffusion flame. It is thin and reasonably steady in its position. Because it is thin, not much heat is lost by radiation. Primarily, heat is lost by conduction through the gas. Accordingly, we might expect its temperature to be slightly below the adiabatic flame temperature. Values of 1800°C–2000°C are typical of such laminar flames. If by cooling or dilution, its temperature drops to about 1300°C it is likely to extinguish. Then, how can a turbulent flame at 800°C–1200°C exist?

Figure 7.14 illustrates the measurement process for laminar and turbulent flames. A probe at a fixed point attempts to measure the flame temperature. The relatively stationary laminar flame is an easy target for the temperature probe. The fluctuating turbulent flame is not. The probe can be in and out of the flame on either the air side or fuel side. A typical trace of the probe output over time is illustrated. Even a small probe may

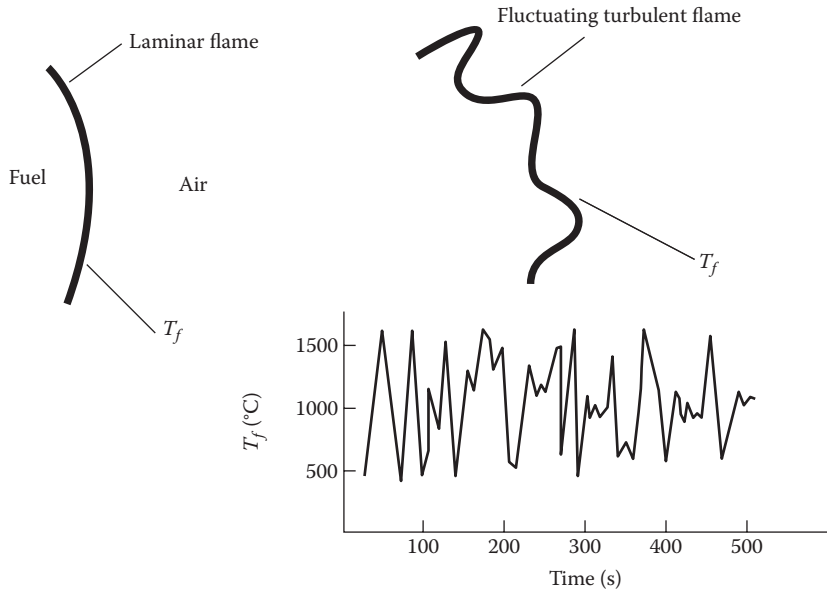

FIGURE 7.14
Measuring flame temperatures.

not respond fast enough in the fluctuating flame so the true maximum and minimum temperatures may not even be realized. The mean time or average temperature is what would be reported in Figure 7.14 for a turbulent flame. The 800°C represents a time-average temperature. If we were capable of "riding" on the fluctuating flame, we would measure temperatures in excess of 1300°C and closer to the laminar flame temperatures. The thermal threat of the turbulent flame is represented by the time-average temperature. That is the temperature an object within or exposed to the turbulent flame would sense from the turbulent flame. So the time-average temperature is very important and is a measure of the damage potential of turbulent flame.

7.7 Flame Lengths for Other Configurations

Up to now, we have primarily focused on pool fire-like flames. Heskestad has said that his flame height formula can also apply to arrays. Others have considered different configurations. These include a fire in the corner, against at wall, on a wall, and impinging on the ceiling. Not surprisingly, the factor Q^* enters into all of these formulas. Some results are couched in terms of the average flame length, and others differentiate between the continuous flame height and the peak height. Hasemi and Tokunaga[6] give results for a square fire in a corner or against a wall; Ahmad and Faeth[7] give results for a fire burning on a wall, and recent Ding[8] give an approximate result for the flame extension along a ceiling from a pool fire below. These results are in terms of Q^* as

$$\frac{L_f}{D} = C_f Q^{*n} - b \tag{7.21}$$

or alternatively in specific units for $\dot{Q}$ in kW and D in m:

$$\frac{L_f}{D} = C'_f \left(\frac{\dot{Q}}{D^{5/2}} \right)^n - b \tag{7.22}$$

Table 7.1 gives the values for C_f, C'_f, and n; and Figure 7.15 describes the configurations. Figure 7.16 gives a graph for all the configurations. The ceiling case should be used when the pool flame is computed as being above the ceiling height.

TABLE 7.1

Flame Length Parameters for Equations 7.21 and 7.22

Configuration	L_f	D	N	C_f	C_f'[a]	b
Pool	Height	Diameter	2/5	3.8	0.23	1.02
Array	Height	$\left(\frac{4\dot{Q}}{\pi\dot{Q}''}\right)^{1/2}$	2/5	3.8	0.23	1.02
Fire in corner	Height	Side of square	2/3	Continuous 3.0 Maximum 4.3	0.028 0.040	0 0
Fire against wall	Height	Side of square	2/3	Continuous 2.2 Maximum 3.5	0.021 0.033	0 0
Fire on wall	Height	Width	2/3	4.9	0.046	0
Ceiling flame	Radius	Diameter of pool fire	2/5	1.6	0.015	0

[a] C_f' in units according to kW and m.

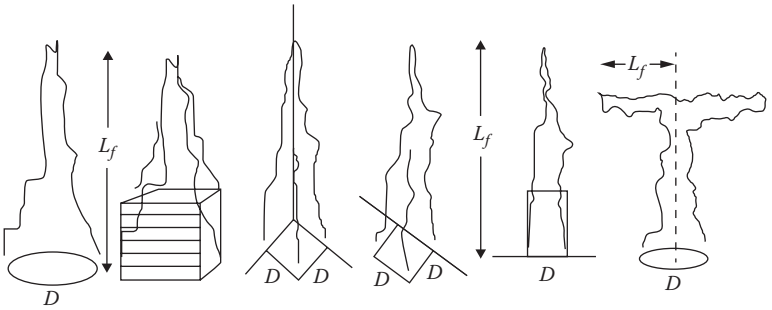

FIGURE 7.15
Flame configurations.

7.8 Whirls and Balls

There are other phenomena related to fire in the free atmosphere. A plume in the wind can lean over, and its length and angle can be computed as a function of Q^* and the Froude number. A wind can also induce a rotation in a plume. This forms a *fire whirl*—a spinning plume. It can happen at the edges of large fire such as forest fires. It can also happen in urban conflagrations, as occurred in 1923 during the fire following the Great Kanto earthquake in Hifukusho-Ato. As the whirl moved off the main fire, it killed 38,000 who were taking refuge near the river. Fire whirls are still the subject of research. According to Saito, Dobashi, and coworkers,[9] the fire whirl achieves a much taller flame than its originating plume due to an increase in burning rate. The swirling motion at the base of the fuel increases the convective heat transfer. Anyone that has seen a fire whirl is amazed at how fast is spins and

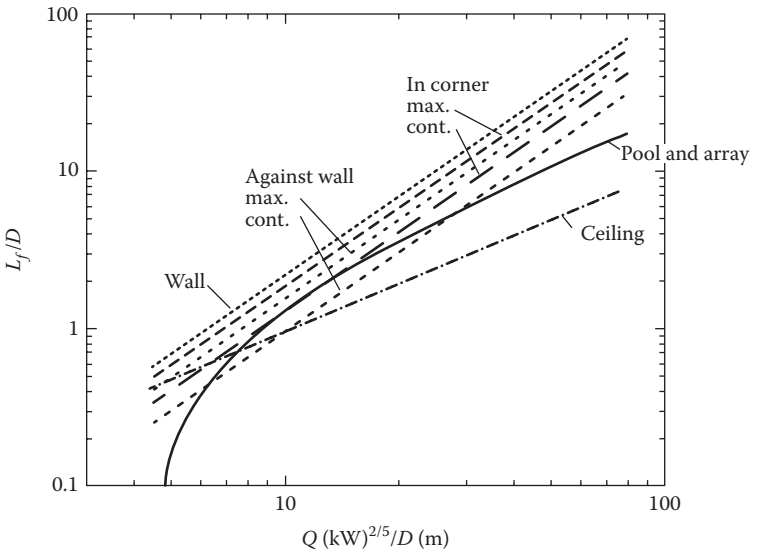

FIGURE 7.16
Flame lengths for various configurations (see Figure 7.15).

its jump in height. A large cylinder, cut in half along vertical lines, and displaced slightly around a centered liquid pool fire, admits a circulating flow to cause a whirl.

Another atmospheric fire phenomenon is a *fireball*. This is often seen in movies after a car careens off a cliff or following an "explosion." In actuality, the car incident is mostly Hollywood. The fireball occurs due to a sudden release of gaseous or aerosol fuel that is ignited. The core of fuel cannot burn all at once; it burns on its edges due to turbulent diffusion. The increase in temperature of the combustion process gives buoyancy, and this carries the raw fuel and burning fuel upward like a burning sphere. Buoyancy distorts the sphere, and turbulence sets in. Just as the flame ends in a plume when the fuel burns out, the fireball stops in the same way. As it rises, it gets bigger and higher; then it is gone. The maximum diameter, its height, and its burning time can all be computed. They are based on the original volume of fuel released. This usually happens when there is a crash or breakage of a tank of gaseous or liquid fuel. The fireballs at the WTC towers on 911 are indicative. Fay and Lewis[10] give simple formulas for the fireball in terms of the original fuel volume. The fuel volume (V_f) should be computed from the mass of fuel released divided by it density at the temperature and pressure of the air.

Height of fireball:

$$L_b\,(\text{cm}) = 12.7[V_f\,(\text{cm}^3)]^{1/3} \tag{7.23}$$

Maximum diameter:

$$D_b \text{ (cm)} = 7.7[V_f \text{ (cm}^3)]^{1/3} \tag{7.24}$$

Burn time:

$$t_b \text{ (s)} = 0.28[V_f \text{ (cm}^3)]^{1/6} \tag{7.25}$$

These simple formulas were derived from theory and laboratory experiments. They work quite well in large-scale events as they are based on sound physics.

7.9 Summary

Buoyancy plays a significant role in natural fire plumes. Buoyancy is a force on the fluid due to gravity and a density or temperature difference. A fire plume is driven by it buoyancy, and a jet flame is driven by the container's exit velocity of the fuel. Turbulent jet flames reach a fixed length according to their pipe diameter. Fire plumes reach a flame height based on the Zukoski number, Q^*. The Zukoski number is the ratio of combustion energy to flow energy in the plume. Turbulent flame temperatures are lower than their laminar counterparts and commonly do not exceed 800°C in moderate size pool fires as measured by thermocouples. But this temperature can increase with fire size, achieving a theoretical maximum rise in air of about 1450°C. These temperatures primarily depend on the radiative fractional loss of the fuel. Because temperatures decrease very rapidly after combustion due to air entrainment, flame height is a critical measure of hazard. Objects above the turbulent flame are not likely to ignite; flame contact is generally required except for remote ignition by radiant heat of very large fires. Formulas were presented, and their origin was guided by the theory of fluids, mainly following that of Bernoulli. Flame height formulas for various configurations were presented, along with formulas for fireball phenomena.

Review Questions

1. For a 500 kW flame compute the flame height if its base is 10 cm and its diameter is 100 cm.
2. A ceiling detector will alarm at a gas temperature of 150°C. For a fire directly under it, at 3 m distance, find the smallest energy release rate fire source that can cause the alarm.

3. Describe how buoyancy occurs and what it depends on.
4. A 0.5 m diameter pool fire has a flame 1 m above a ceiling of 3 m tall. What is the energy output of this fire?
5. For the problem in 4, compute the radial extent of the flame under the ceiling.

True or False

1. Although a turbulent flame temperature is roughly 800°C, the temperature at the fluctuating flame tip is no more than 350°C.
2. Eddies or vortexes are rotating regions of flow.
3. Gasoline fires are much hotter than wood fires.
4. The velocity of gasoline vapors leaving the surface of a liquid pool fire originates at 3 m/s or more.
5. Theoretically, a buoyant plume can rise forever in a cold atmosphere.
6. A fire whirl is a ride in an amusement park.
7. A fireball can occur if a dump of gaseous fuel is suddenly ignited.
8. Buoyancy can only occur in a container such as a balloon.
9. A Froude number for a plume is about 1.5.
10. The parameter Q^* has some strange units.

Activities

All these experiments need to be done in a safe laboratory site and with attention to fire spread and its extinguishment.

1. Observe buoyant plumes in the atmosphere from smoke stacks, fires, or other sources. Note their nature, eddy characteristics, and how they are affected by wind.
2. Make a cylindrical shape about 2 ft in diameter and 2 ft high, and cut it vertically to make two equal parts. Put a small pan (about 2–3 in. in diameter), ignite it, and surround the flame with the two cylinder pieces, displaced slightly to form two vertical gaps. As the air is drawn into the gaps to be entrained into the fire plume it will create a fire whirl.
3. In a laboratory setting under a hood, ignite a small pan of heptane or similar flashpoint liquid fuel. Use a pan no larger than 10 in. in diameter. Observe the fluctuations of the flame, its necking in at its base, and the eddy vortices.

4. Fill a balloon with natural gas or methane. Attach a string to the balloon. Wet the string with a flammable liquid to form a wick. Tie the balloon to safe point and ignite the string. As the flame moves to the balloon and bursts it, a fireball will occur.
5. Use a square pan about 2 in. on a side. Ignite it in an open space, then against a wall, then in a corner. Observe the flame height and check if it follows the formulas.

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8

Combustion Products

Learning Objectives

Upon completion of this chapter, you should be able to

- Explain the nature and levels of combustion products for various fire conditions
- Explain the property called yield and how it relates to concentration of that product in smoke
- Calculate the hazards of combustion products in smoke
- Explain the role of equivalence ratio in producing combustion products

8.1 Introduction

We have seen that the mass burning rate is a significant quantity that results from the burning rate flux ($\dot{m}''$) and the area (A) involved in burning due to ignition and spread: $\dot{m} = \dot{m}''A$. From this burning rate ($\dot{m}$), we can derive all the products that result from the fire's chemical reaction. We have seen that energy release rate ($\dot{Q}$) is derived as $\dot{m}\Delta H_c$, where ΔH_c is the heat of combustion. $\dot{Q}$ controls the smoke temperature and the surrounding heat flux. It causes an immediate effect on its surroundings. All of the other products of the fire's chemical reaction are frozen in the *smoke* emanated in the buoyant plume leaving the fire. (*Smoke* here is defined as the gases and particulates that flow in stream from the flame.) As with $\dot{Q}$ proportional to $\dot{m}$ by ΔH_c, the rates of production of the other products are proportional to $\dot{m}$ according to the fire's chemical reaction. This proportionality is called the *yield* for each product species. These products of combustion involve carbon dioxide and water vapor for the *complete burning* of hydrocarbon fuels; however, other products are possible due to *incomplete combustion* or due to the presence of

other elements, besides carbon, hydrogen, and oxygen, in more complex fuels. These incomplete combustion products can have a variety of harmful effects on people, on commodities, and on equipment. Usually, the harm or damage is related to the concentration of combustion product and its exposure over time. In this chapter, we present quantitative criteria for several products of combustion. An elementary background in chemistry is required.

8.2 Scope of Combustion Products

The nature of the combustion products depends on the fuel composition and on the fire process. We have seen that fire can be characterized as (1) a premixed flame, (2) a diffusion flame, and (3) smoldering or surface oxidation. Only diffusion flames and smoldering, to some degree, are considered in this chapter. Ultimately, we need to represent the chemical reaction occurring in the fire process. This reaction depends on the completeness of combustion. For example, if we burned methane in air (recall 1 mol of air is 0.21 mol of O_2 and 0.79 mol of N_2), we can write the following chemical equation:

$$CH_4 + \frac{(4)}{0.42}(0.21\,O_2 + 0.79N_2) \rightarrow CO_2 + 2H_2O + \frac{(4)(0.79)}{0.42}N_2$$

For *complete* or *ideal* combustion, the products, by definition, are the most stable compounds: CO_2 (carbon dioxide) and H_2O (water). At combustion temperatures, these species are gases, although the water could condense if it finds a cool surface. The coefficients of each term in the chemical equation have been deduced so that atoms are not destroyed (e.g., 1 C atom and 4 H atoms in CH_4). From this balance of atoms (or mass), we can compute for every 16 g of CH_4 (recall that 1 mol of CH_4 has a mass of 16 g, 12 g for C and 1 g for each H) that we must have (4)/0.42[0.21(32) + 0.79(28)] or 274.7 g of air. (Note that 1 g of air has about 0.23 g of O_2 and 0.77 g of N_2.) These proportions insure that all of the methane and oxygen are completely consumed in the reaction. The ratio of this mass of air to mass of fuel is called the (*ideal) stoichiometric air-to-fuel mass ratio* (*s*), that is,

$$s = \frac{274.7\text{ g air}}{16\text{ g }CH_4} = 17.2\text{ g air/g fuel}$$

If more air is available, the condition is said to be *overventilated* or the process is *fuel lean*. For less air than required for stoichiometric burning, the process is termed *underventilated* or *fuel rich*. All of the oxygen in that air is reacted

by the time the smoke leaves the flame. In all cases, the nitrogen in the air is passive and remains constant. However, it will be heated as a result of the chemical reaction's energy release.

Typical fuels involved in fire processes are hydrocarbons, that is, they are composed of hydrogen (H) and carbon (C). Other fuels may also include oxygen (O), nitrogen (N), chlorine (Cl), fluorine (F), and bromine (Br). The resultant combustion products depend on the process, as illustrated in Figure 8.1. In an ideal complete reaction, the N, Cl, F, and Br would yield their respective gases. However, in any fire process, the reaction is not complete and the resultant gases are normally hydrogen cyanide (HCN), hydrogen chloride (HCl), hydrogen fluoride (HF), and hydrogen bromide (HBr), respectively. In addition, incomplete combustion leads to carbon monoxide (CO) in place of carbon dioxide (CO_2), soot (principally carbon), and many hydrocarbons (HCs) as a result of the thermal decomposition of the original fuel. Gaseous hydrogen can also be found in incomplete combustion processes. Figure 8.1 shows the various fire processes and the associated products of combustion. It is very important to recognize the particular fire process because the products of combustion depend on the process as well as on the fuel. Smoldering requires very little air to maintain. Its combustion is incomplete resulting in a significant yield of CO.

Initially, there is sufficient air available in a room fire to support flaming combustion. If fire occurs in a closed room, the oxygen in the air will be expended and the process becomes underventilated. A small opening to the

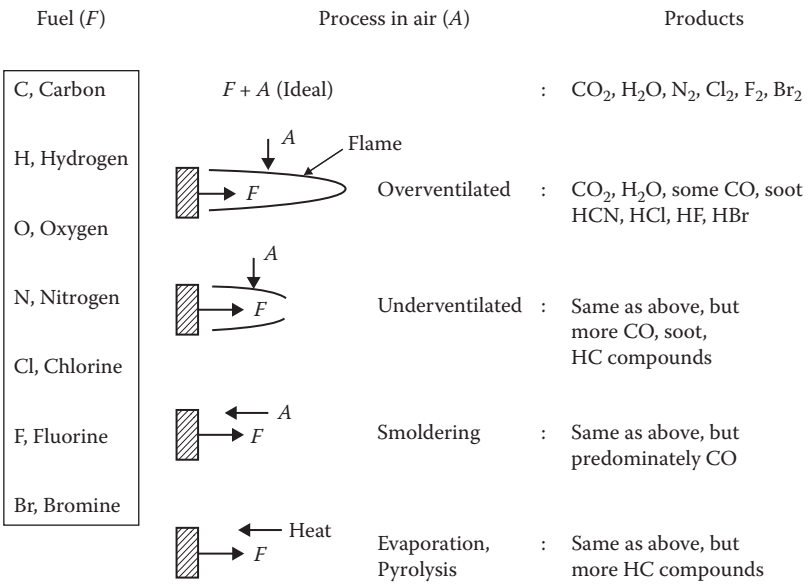

FIGURE 8.1
Typical products of combustion in fire.

room will bring in some air, but if the fuel generated is too great, the fire will remain underventilated. Extinction will generally occur when the oxygen feeding the fire is about 11% or less (less for higher room temperatures).

The parameter that quantitatively represents the over- and underventilation states is called the *equivalence ratio*, Φ, defined as the mass ratio of fuel (gas) available to air available times the stoichiometric ratio, s.

$$\Phi = \left(\frac{\text{mass of fuel (gas)}}{\text{mass of air}} \right) \times s \tag{8.1}$$

That is, if $\Phi > 1$, the fire is underventilated. For $\Phi > 1$, these decomposition products are not burned to completion. For $\Phi < 1$, there is sufficient air and the process will be complete: This case is said to be overventilated. All fires start with $\Phi < 1$ and with continued growth can reach $\Phi > 1$ states. The chemistry of these processes is complex, and consequently, empirical data must be used to quantify the nature of the combustion products for each fuel. These predictions by fundamental modeling are difficult and still the subject of much research.

8.3 Yields

As the heat of combustion gives us the energy release per unit mass of fuel burned, *yields* give us the mass production of each product species per unit mass of fuel burned. Just as the heat of combustion for a fire reaction is not the complete ideal value and must be measured, so too is the yield of a species. Calorimetry devices serve to measure both the actual heat of combustion and the yields. For example, the *yield of CO* is defined as

$$y_{CO} = \frac{m_{CO}}{m} \tag{8.2}$$

where m_{CO} is the mass of CO produced and m is the mass of fuel burned. Alternatively, we could consider the rates of mass, that is, $y_{CO} = \dot{m}_{CO}/\dot{m}$, where $\dot{m}$ is the rate of burning and $\dot{m}_{CO}$ is the rate of CO mass produced. It is generally accepted that the yields are fairly constant for a given fuel as long as $\Phi < 1$. But as the fire condition becomes underventilated, the yields change.

Tewarson[1] of FMGlobal has nearly single-handedly established a wealth of consistent data on the yields of various fuels. Although mainly derived from relatively small-scale tests but over a realistic range of oxygen and heating for fire, it is generally accepted that these results apply to realistic fire

TABLE 8.1

Fuel Properties as a Function of Ventilation

Conditions	Overventilated Conditions						Underventilated		
Fuel	y_{CO_2} (g/g)	y_{CO} (g/g)	y_{soot} (g/g)	ΔH_c (kJ/g)	$\Delta H_{c,ideal}$ (kJ/g)	D_m (m²/g)	y_{CO} (g/g)	y_{H_2} (g/g)	y_{HCl} (g/g)
Gases									
Propane	2.85	0.005	0.024	43.7	46.4	0.155	0.229	0.0110	0
Acetylene	2.60	0.042	0.096	36.7	48.2	0.315	NA[a]	NA	0
Liquids									
Ethyl alcohol	1.77	0.001	0.008	25.6	26.8	NA	0.219	0.0098	0
Heptane	2.85	0.010	0.037	41.2	44.6	0.190	NA	NA	0
Solids									
Wood (red oak, pine)	1.27	0.004	0.015	12.4	17.7	0.037	0.138	0.0024	0
Polymethyl methacrylate (PMMA)	2.12	0.010	0.022	24.2	25.2	0.109	0.189	0.0032	0
Polystyrene (PS)	2.33	0.060	0.164	27.0	39.2	0.335	NA	NA	0
Nylon	2.06	0.038	0.075	27.1	30.8	0.230	NA	NA	0
Polyurethane (PU) flexible foam	1.51	0.031	0.227	19.0	27.2	0.326	NA	NA	0
Polyvinyl chloride (PVC)	0.46	0.063	0.172	5.70	16.4	0.400	0.360	NA	0.4

Source: Based on data from Tewarson, A., Generation of heat and chemical compounds in fires, Chap. 3-4, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

[a] NA, not available.

conditions. Table 8.1 lists a sample of his data for representative fuel classes: gases, liquids, and solids. The yields are shown for CO_2, CO, and soot along with the measured heat of combustion, ΔH_c. These are experimentally derived values representative of over- and underventilated fire process. The ΔH_c is less than its ideal value that would occur for the ideal complete reaction, as indicated in Table 8.1. The table also gives the yields of hydrogen (H_2) and hydrogen chloride (HCl) for PVC plastic containing chlorine. The quantity D_m relates to visibility, and we will come back to it later in the chapter.

In most cases, the yields (or negative yields, as in the consumption of oxygen) are slightly less than their ideal chemical reaction values for CO_2, H_2O, and O_2. The yields associated with the products of incomplete combustion (e.g., CO, soot) are relatively small. But as we shall see, these are the culprits that do the damage. Carbon monoxide can kill, HCl can corrode metal, and soot can damage.

Some typical underventilated values of yields for CO and H_2 are listed in Table 8.1, but their precise values depend on Φ. For $\Phi < 1$, the overventilated values in Table 8.1 apply. Figure 8.2 displays how the underventilated yields vary with Φ. They are represented as a ratio of the yield to its overventilated

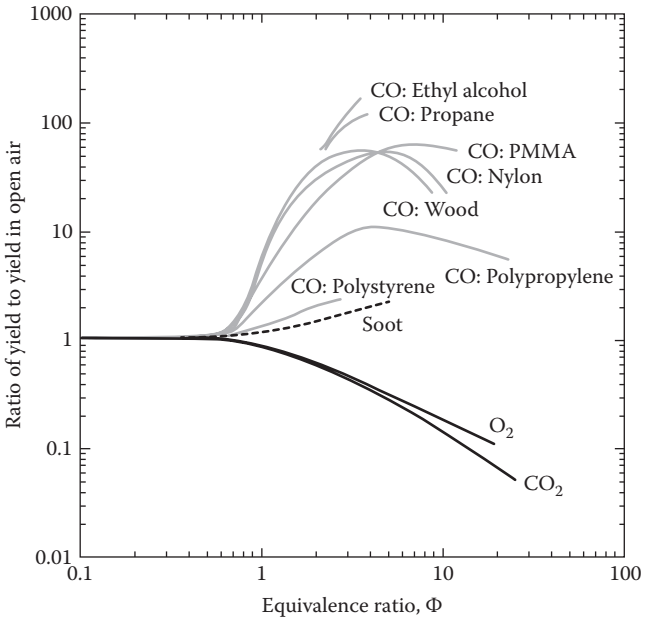

FIGURE 8.2
Effect of underventilation on yields for many materials—approximate representation of data. (After Tewarson, A., Generation of heat and chemical compounds in fires, Chap. 3-4, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.)

value. This graph comes from Tewarson[1] and is very valuable. For example, it can explain how carbon monoxide is increased as the fire becomes underventilated (a state sometimes called *ventilation limited* in compartment fires). Also, the results show that CO yields depend on fuel, but the yields (±) of O_2, soot, and CO_2 are essentially fuel independent when plotted as $y_{underventilated}/y_{overventilated}$ versus Φ.

Example 8.1

Let us consider an example. In Chapter 6, we computed the burning flux of wood and polystyrene (PS) as 11 and 38 g/m²-s. Suppose we have the same size fire for each fuel: say 2000 kW. Since (from Equation 6.2)

$$\dot{Q} = \dot{m}'' A \Delta H_c$$

the fuel areas involved can be computed as

$$A = \frac{\dot{Q}}{\dot{m}'' \Delta H_c}$$

For wood

$$A = \frac{2000 \text{ kW}}{(11 \text{ g/m}^2\text{-s})(12 \text{ kJ/g})} = 15.2 \text{ m}^2$$

and for PS

$$A = \frac{2000 \text{ kW}}{(38 \text{ g/m}^2\text{-s})(27 \text{ kJ/g})} = 1.9 \text{ m}^2$$

Fire in open air: overventilated. For a fire in the open air (free burning and overventilated as ample air is available) or in a large room with sufficient open windows, the overventilation yields apply. The production rate of CO is then computed by

$$\dot{m}_{CO} = y_{CO} \dot{m}'' A, \tag{8.3}$$

or for wood

$$\dot{m}_{CO} = (0.004)(11 \text{ g/m}^2\text{-s})(15.2 \text{ m}^2) = 0.67 \text{ g/s}$$

and for PS

$$\dot{m}_{CO} = (0.060)(38 \text{ g/m}^2\text{-s})(1.9 \text{ m}^2) = 4.3 \text{ g/s}$$

As a result, we see more CO is produced by PS.

Fire in a room that is underventilated. What if these same fires are in a room where the air supply through windows is 500 g/s, typical of a small broken window? Let us calculate Φ from the room to examine the degree of underventilation. For this computation, we need the stoichiometric ratio of air to fuel required for burning, *s*. Let us estimate *s* from the ideal reaction using ΔH_c, ideal, which is derived as follows:

$$s \approx \frac{\Delta H_{c,ideal}}{3 \text{ kJ/g}_{\text{air}}} \tag{8.4}$$

where the approximation of a constant energy release for burning the oxygen in air is used. For most ordinary combustibles, approximately 3 kJ is released for each gram of air used by the fire reaction. Then, for wood

$$s = \frac{17.7}{3} = 5.9 \text{ g air/g wood}$$

and for PS

$$s = \frac{39.2}{3} = 13.1 \text{ g air/g PS}$$

The corresponding Φ values are (fuel to air available times *s*)

$$\Phi_{wood} = \frac{(11 \text{ g/m}^2\text{-s})(15.2 \text{ m}^2)(5.9)}{(500 \text{ g/s})} = 1.97$$

and

$$\Phi_{PS} = \frac{(38 \text{ g/m}^2\text{-s})(1.9 \text{ m}^2)(13.1)}{(500 \text{ g/s})} = 1.9$$

From Figure 8.2 and the overventilated values from Table 8.1, we can estimate that for wood at Φ = 1.97: (Table 8.1 gives the overventilated yield as 0.004, and Figure 8.2 reads approximately $y_{underventilated}/y_{overventilated} \sim 50$.)

$$y_{CO} \approx 50\ (0.004) \approx 0.20$$

and for PS at Φ = 1.9:

$$y_{CO} \approx 2.0\ (0.060) \approx 0.12$$

The amount of CO produced has only doubled for the PS but has increased by 50 times for the wood for this particular room fire condition. This example

should illustrate that CO production depends on the fuel as well as the air supply. For the wood CO yield of 0.2, this state would give a CO production rate of 33.4 g/s provided the burning rate of the wood can be maintained at 11 g/m^2-s at this underventilated state. Similarly, the production rate of the PS is 8.7 g/s for this unventilated case. The wood fire in the underventilated state has become more hazardous than the PS with this higher production rate of CO. Notice a lot more wood is burning here than PS.

Finally, it should be pointed out that smoldering, especially the notorious fire scenario of a cotton or polyurethane foam mattress or sofa, produces CO yields of as high as 0.2–0.3. These yield levels are comparable to the underventilation values in flaming for fuels. But the production rate in smolder is much less than generally that of underventilated fires. This is why they take a long time to do harm. A growing fire going through flashover to a ventilation-limited state can suddenly produce toxic smoke.

8.4 Concentrations

Yields measure what is produced at the fire source. The principal hazard of fire is the composition and associated concentrations of harmful species in the smoke. By *smoke,* we mean the gas stream that flows away from the fire (as illustrated in Figure 8.3) continuing to mix with air and with having no further chemical reactions. The amount of mixing with air determines the concentration of a particular species *yielded* in the flame. Associated with each species yield, we have a corresponding concentration at different points

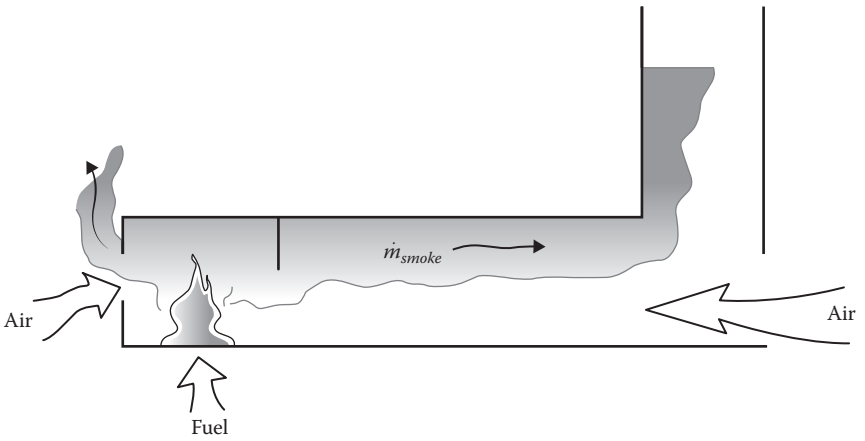

FIGURE 8.3
Illustration of smoke movement from a fire.

in the smoke. Moreover, associated with the energy yield, ΔH_c we have the concentration-like variable, temperature at each point in the smoke. The species concentration will decay as air is entrained into the smoke. Some species, like temperature, decay as well due to losses of mass as the smoke encounters clean, cold surfaces. For example, soot is deposited, and HCl (gas) can condense on surfaces. This surface transfer is increased as the local smoke velocity increases; that is why heavy depositions of soot are seen around door cracks as the smoke squirts through at high velocity. In addition, soot is transported by both a concentration and temperature difference. The latter is called thermophoresis and mainly responsible for soot deposition early in a fire onto cold surfaces. Objects adjacent to a flame can have these deposits subsequently burn off.

Concentration can be expressed in several ways. Mass concentration is defined as

$$Y_{species} = \frac{\dot{m}_{species}}{\dot{m}_{smoke}} = \frac{y_{species}\dot{m}}{\dot{m}_{smoke}} \quad \text{g species/g smoke} \tag{8.5}$$

where $\dot{m}_{smoke}$ is the mass flow rate of the smoke. Usually, concentrations are represented as volume fractions, that is, the volume occupied by the species at normal atmospheric temperature and pressure to the corresponding smoke volume. For example, if we could extract an individual species and let it expand in normal atmospheric pressure, then its volume compared to the volume resulting from extracting the entire smoke mixture is volume fraction. This volume fraction can be estimated as

$$X_{species} = \frac{(29 \text{ mol of smoke per g of smoke})Y_{species}}{(M_{species} \text{ mol of species per g of species})} \tag{8.6}$$

in moles (or volume) of species per moles (volume) of smoke

where $M_{species}$ is the molecular weight of the species, and 29 is an approximate molecular weight of the smoke (since it mostly contains N_2, 28 g/mol).

Example 8.2

In the previous example for production of CO from the PS fire, the flow rate of the smoke flow leaving the room must balance the fuel and air flow rate, so that $\dot{m}_{smoke}$ = 500 g air entering + (38 g/m^2-s)(1.9 m^2) fuel supplied ≈ 572 g/s.

Therefore, from Equations 8.3 and 8.5, for the underventilated case

$$Y_{CO,\,under} = \frac{(0.12)(38 \text{ g/m}^2\text{-s})(1.9 \text{ m}^2)}{572 \text{ g/s}} = 0.015 \text{ or } 1.5\%.$$

The corresponding volume concentrations is computed as

$$X_{\mathrm{CO},\,under} = \frac{(1.5\%)(29)}{(28)} = 1.56\%$$

If an overventilated yield for PS were used in error, the overventilated case would give concentrations of

$$Y_{\mathrm{CO},\,over} = \frac{4.3\ \mathrm{g\ CO/s}}{572\ \mathrm{g/s}} = 0.0075 \text{ or } 0.75\%$$

and

$$X_{\mathrm{CO},\,over} = \frac{(0.75\%)(29)}{(12+16)} = 0.78\%.$$

Let us examine the hazard these concentrations of CO present. It is common to express low concentrations (by volume) in terms of *parts per million* (*ppm*). For example, the CO volume fraction given above as 0.0075 is 7500 ppm because $0.0075 = 7500/10^6$.

In general, if $\dot{m}_a$ is the mass flow rate of air into a room and $\dot{m}$ is the rate of fuel supplied, it can be shown that the mass concentration is directly related to the yield from Equation 8.5 as

$$Y_{species} = \frac{\dot{m}_{species}}{\dot{m}_{smoke}} = \frac{y_{species}\dot{m}}{\dot{m}_{smoke}} = \frac{y_{species}\dot{m}(s/\dot{m}_a)}{(\dot{m}_a + \dot{m})(s/\dot{m}_a)}$$

$$Y_{species} = y_{species}\left(\frac{\Phi}{s+\Phi}\right). \tag{8.7}$$

Here, Φ is based on air and fuel supplied, Equation 8.1, and the stoichiometric ratio, s, of the fuel. So for a given fuel, there is a one-to-one correspondence between yield and concentration at a given equivalence ratio. As the equivalence ratio increases toward 1 and more, the concentration increases sharply. As the hazard is related to concentration and exposure time, survivability diminishes.

8.5 Hazards

Each concentration of species can present a specific hazard. The hazard can be to humans, to equipment, and to property. Here, we consider only the hazard to humans. However, essentially in each case, the hazard is measured by the duration of the concentration exposed. Below a threshold concentration, nothing is damaged. Here, we use concentration in a general sense. It can include temperature, the reduction in oxygen (vitiation, $0.21 - X_{O_2}$), as well as specific harmful combustion product concentrations such as carbon monoxide, X_{CO}.

Combustion products such as soot and odor-bearing hydrocarbons can destroy significant quantities of goods, even when the actual fire damage by heat is small. Soot ladened with HCl or other acid gases (e.g., HBr, HF) can deposit on equipment. If not cleaned, this acidity can cause considerable damage later through corrosion. Such effects on goods and equipment, we do not pursue further.

We draw from the review by Purser[2] to examine toxicity effects.

8.5.1 Narcotic Gases

Narcosis is the state of induced sleep, which reduces the capability of escape and can lead to death. It can be caused by the combustion gases CO (carbon monoxide), HCN (hydrogen cyanide), and even CO_2 (carbon dioxide) at high concentrations. It can also be induced by the reduction of oxygen to low concentrations. All animals require oxygen to be transported in the body by oxyhemoglobin (O_2Hb) in the blood. The introduction of CO into the lungs causes the hemoglobin to attach instead to the CO as carboxyhemoglobin (COHb), which prevents oxygen in the blood from attaching. The introduction of HCN affects the cells and also prevents oxygen from being used by the body. Roughly, all of these effects are additive, so that if you are half dead from CO, 3/8 dead from HCN, and 1/8 dead from the reduction of oxygen, you are dead in accordance with the additivity of narcosis effects.

Figure 8.4 shows the time to reach loss of consciousness for exposure to HCN and CO in primates for a specific activity level. We see from this figure that HCN is more toxic: It requires much less concentration to cause unconsciousness. Also the threshold levels below which no loss of consciousness occurs is about 90 ppm for HCN and 900 ppm (or 0.09%) for CO. Below these levels, incapacitation is still possible, but not unconsciousness. Table 8.2 shows the effect of oxygen loss due to oxygen or carbon monoxide on humans. Incapacitation can occur at as low as 8%–12% O_2 and 0.015%–0.040% CO corresponding to 20%–40% COHb. Usually, 40% COHb indicates an incapacitation level and 60% COHb a lethal state. These levels are not precise and can vary in humans depending on health and other factors.

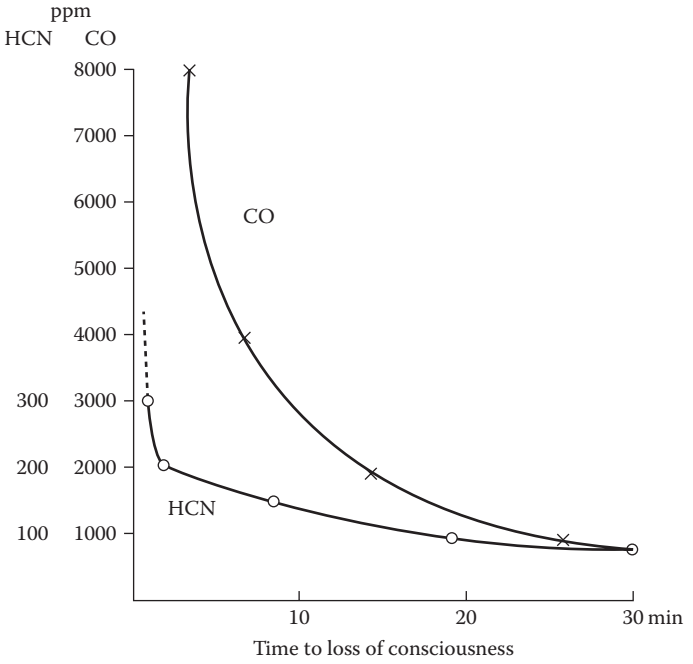

FIGURE 8.4
Time to unconsciousness in primates by exposures to CO or HCN. (After Purser, D.A., Toxicity assessment of combustion products, Sect. 8, Chap. 2, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.)

TABLE 8.2

Effects of O_2 Loss in Blood

Loss due to Decrease in Oxygen Concentration		Loss due to Increase in Carbon Monoxide Concentration		
O_2Hb (%)	X_{O_2} (%)	COHb (%)	X_{CO} (%)	Effect
90–100	15–21	0–10	<0.008	None
80–90	12–15	10–20	0.008–0.015	Fatigue
60–80	8–12	20–40	0.015–0.04	Dizziness, nausea, possible paralysis
50–60	6–8	40–50	0.04–0.06	Prostration, asphyxiation, collapse
30–50	3–6	50–70	0.06–0.3	Unconscious in minutes, death
0–30	0–3	70–100	>0.3	Unconscious in seconds, death likely

Source: Based on data from Purser, D.A., Toxicity assessment of combustion products, Sect. 8, Chap. 2, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

TABLE 8.3

RMV (Liters/Minute) for a 70 kg Man

RMV	Activity
8.5	Resting
25	Light work
50	Heavy work, slow running

Source: Based on data from Purser, D.A., Toxicity assessment of combustion products, Sect. 8, Chap. 2, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

Carbon monoxide is the leading killer of people in fire, principally because of the long-time exposure from smoldering fires (usually > 1 hour) or because of rapid fire growth resulting in an underventilated fire. An approximate formula that shows the effect of exposure to CO over time is given in terms of the resultant COHb:

$$\text{COHb}\ (\%) \approx 0.33\text{RMV} \cdot X_{\text{CO}}\ (\%) \cdot t\ (\text{min}) \tag{8.8}$$

where

t is the exposure time in minutes

X_{CO} is the volumetric CO concentration in %

RMV is the respiration minute volume or inhalation rate in liters/min

Table 8.3 gives typical RMV values. The significance of Equation 8.8 is that the damage property (COHb) depends on the exposure quantity ($X_{\text{CO}}t$) and the respiration rate (RMV). Not only does activity effect RMV, but so does the exposure to CO_2, a plentiful combustion product. Table 8.4 shows the effects of CO_2, both on RMV and on narcosis. An increase in CO_2 uptake increases the respiration rate. So as a fire produces more CO and CO_2, the hazard to humans and animals increase.

In a fire smoke environment with a hydrocarbon fuel, the atmosphere can contain CO_2, reduced O_2, and CO. All three accumulate to induce narcosis due to reducing oxygen in the body, hypoxia. If atomic nitrogen (N) is contained in the fuel, HCN will be produced and it too adds to the narcosis. It is believed that commonly CO is the predominant cause of death due to fire smoke, but HCN can be a significant contributor. By the time CO_2 and O_2 become hazardous, the CO and HCN effects have done their damage.

8.5.2 Additive Fractional Incapacitation Doses

The narcotic gases can combine to harm in an additive manner. While CO alone may not incapacitate or harm, the other gases can contribute to do so. A model to account for these effects is based on the concept of a fractional

TABLE 8.4

Effects of CO_2 on Humans at Normal Atmospheric Pressure and O_2 Concentration

CO_2 Concentration in Inhaled Air (%)	Effect
0.04	Negligible, level in normal air
0.5	Safe limit, prolonged exposure
1.8–2.0	30%–50% increase in ventilation rate
2.5–3.0	100% increase in ventilation rate
4.0	300% increase in ventilation rate
5.0	Dizziness, poisoning symptoms, >30 minutes
7.0–9.0	Unconscious, in 15 minutes
10.0–30.0	Unconscious, in <10 minutes, followed by death

Source: Purser, D.A., Toxicity assessment of combustion products, Sect. 8, Chap. 2, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

incapacitating dose for each. *Dose* is the accumulation of the species in the body over time. The *fractional dose* is the actual dose divided by its corresponding incapacitating dose. For example, very approximately from Figure 8.4, at 10 minutes the incapacitating dose of HCN is about (130 ppm × 10 minutes) and for CO about (2700 ppm × 10 minutes). So we might take the approximate incapacitating dose as about 0.13%-min for HCN and 2.7%-min for CO. Suppose in a fire exposure for an individual, the accumulated doses were 0.026%-min for HCN and 2.16%-min for CO. The fractional doses for each would be 0.20 for HCN and 0.80 for CO. Adding to 1 means that the two combine to incapacitate the individual exposed. Adding to more than 1 definitely means incapacitation and possible death.

The process is more complicated than this example. There are factors to consider: (1) variations in incapacitating doses for individuals, (2) the accuracy of the model, and (3) other biological and toxicological complexities. Purser[2] ably describes many of these factors.

8.5.3 Irritant Gases

Irritant gases consist of the acid gases HCl, HF, HBr, and other hydrocarbon by-products, such as acrolein and formaldehyde which can be derived from wood. These gases can be painful to the eyes and air passages and can reduce the walking speed in escape. They are not likely to be fatal during inhalation. Postexposure fatality is, however, possible. Pulmonary damage can result in death up to a day following exposure. It is also possible that these gases tend to reduce the RMV.

8.5.4 Smoke Visibility

Smoke visibility is perhaps the first perceived hazardous effect in a fire, even before the smoke becomes a serious thermal threat. Light is attenuated by smoke due to particles, mainly soot, but also due to tarry condensables. Soot gives smoke a black color. Tars, generated by heating in an ample air supply, give smoke its whitish color. White smoke likely means unburned fuel and condensables present in the smoke. The property that measures the attenuation (absorption and scattering) in smoke is the extinction coefficient, κ_s. κ_s is measured in m^{-1}. It can be used to compute the reduction in light intensity, I, over a light path length, l. The original intensity, I_o is reduced by the smoke to

$$I = I_o \exp(-\kappa_s l) \tag{8.9}$$

If the extinction coefficient is 1 m^{-1} and the path length is 2 m, the intensity of the light will be reduced about 13.5% of its original value.

Sometimes this equation is presented in the fire smoke literature as based on the power of 10, and the optical density per unit path length is used instead of the extinction coefficient.

The ability to see through smoke is called *visibility*, L_v, and is related to κ_s. Figure 8.5 shows the relationship between these variables. L_v is the maximum distance an object can be seen and recognized through the smoke. The extinction coefficient is related to a property called the mass optical density (D_m). The mass optical density is typically measured and reported in the fire literature. It represents the extinction of visible light due to solid and liquid particulates in the smoke. This property has been tabulated in Table 8.1. The extinction coefficient depends on the concentration of the

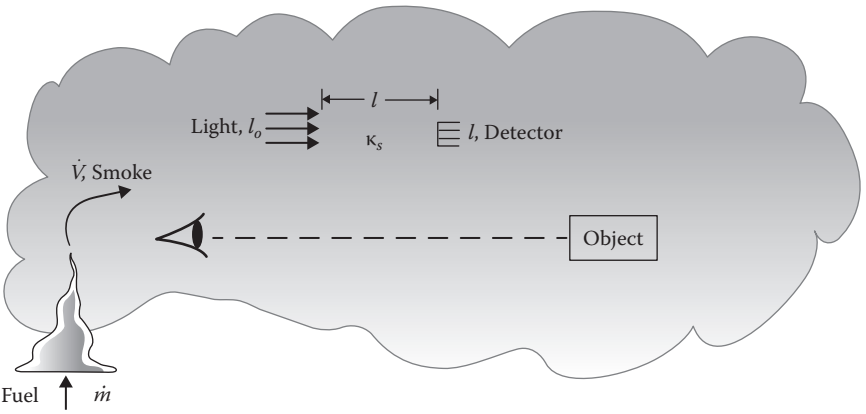

FIGURE 8.5
Smoke attenuation and visibility.

smoke particulates and can be computed for a given burning rate ($\dot{m}$) and smoke volumetric flow rate $\dot{V}$. It is related through these variables to the mass optical density for a case of flowing smoke as

$$\kappa_s = \frac{\dot{m} D_m}{\dot{V}}, \tag{8.10}$$

or for a static case where m is the mass of fuel burned in a closed volume, V

$$\kappa_s = \frac{m D_m}{V}. \tag{8.11}$$

For each value of κ_s, there is a corresponding visibility, which is given in Figure 8.6 as approximately

$$L_v = \frac{C_v}{D_o} \tag{8.12}$$

where D_o is the optical density per unit path length and is an alternative parameter to the extinction coefficient. In fact, $\kappa_s = 2.3\, D_o$ and C_v ranges from 1 to 4 m^3/g depending on the illumination of the object. The range of results

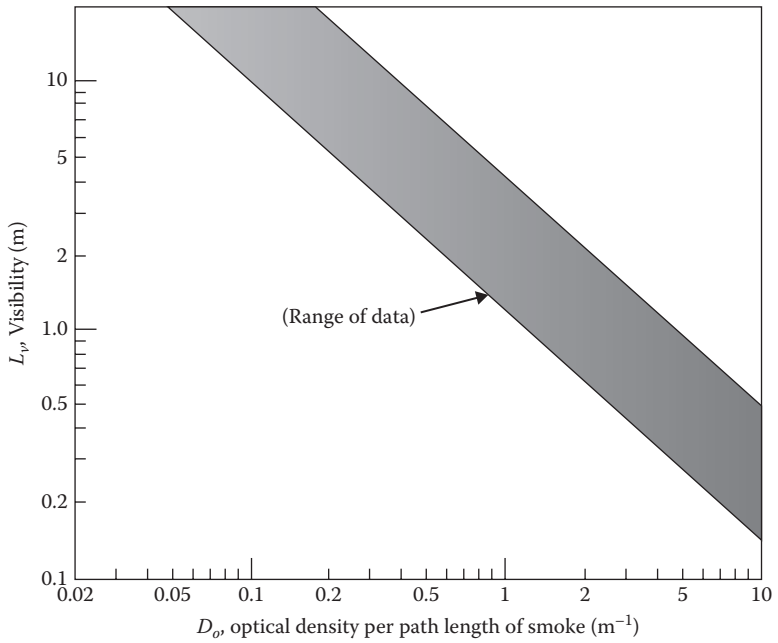

FIGURE 8.6
Smoke visibility in terms of optical density per path length. (After Quintiere, J.G., *Fire Mater.*, 6(3, 4), 145, 1982.)

shown in Figure 8.6 was developed from various experiments using people to sight objects through smoke from different fires. The results vary due to human interpretation and on the way the sighted object was illuminated.

Example 8.3

Let us consider an extension to our previous example for the PS in the underventilated room fire. Assume the smoke has cooled to normal air temperatures so that the density (ρ) of the cool gas mixture is approximately 1.0 kg/m^3.

For the PS fuel burning underventilated in the room

The PS, the volumetric flow rate is

$$\dot{V} = \frac{\dot{m}_{smoke}}{\rho} = \frac{500\ \text{g/s} + 38\ \text{g/m}^2\text{-s} \times 1.9\ \text{m}^2}{1\ \text{kg/m}^3 \times 10^3\ \text{g/kg}} = 0.572\ \text{m}^3/\text{s}$$

Table 8.1 only gives D_m for the overventilated case as D_m = 0.34 m^2/g. As the extinction coefficient is related to soot concentration, we take

$$\frac{D_m}{D_{m,over\text{-}ventilated}} = \frac{y_{soot}}{y_{soot,over\text{-}ventilated}}$$

For PS at Φ = 1.9, approximating the soot yield ratio in Figure 8.2 as 1.5, and using Table 8.1, we find for the underventilated fire,

$$D_m = 0.335\ \text{m}^2/\text{g} \times 1.5 = 0.503\ \text{m}^2/\text{g}.$$

Equation 8.10 gives

$$\kappa_s = \frac{38\ \text{g/m}^2\text{-s} \times 1.9\ \text{m}^2 \times 0.503\ \text{m}^2/\text{g}}{0.572\ \text{m}^3/\text{s}} = 63.5\ \text{m}^{-1}$$

The smoke visibility is then computed from Equation 8.11 as

$$L_v = (1 \text{ to } 4\ \text{m}^3/\text{g}) \times 2.3/63.5\ \text{m}^2/\text{g} = 0.036 \text{ to } 0.145\ \text{m}$$

or about 4–15 cm: This is poor visibility.

For the wood fuel burning underventilated in the room

Note that the same unventilated computation for the wood fire at Φ = 1.97 gives

$$\kappa_s = \frac{11\ \text{g/m}^2\text{-s} \times 15.2\ \text{m}^2 \times 1.5 \times 0.037\ \text{m}^2/\text{g}}{0.667\ \text{m}^3/\text{s}} = 13.9\ \text{m}^{-1}$$

and

$$L_v = (1 \text{ to } 4\ \text{m}^3/\text{g}) \times 2.3/13.9\ \text{m}^2/\text{g} = 0.17 \text{ to } 0.66\ \text{m}\cdot$$

This wood smoke is somewhat clearer than the PS case, but visibility is still poor. However, these were big fires of 2000 kW.

Suppose the wood fire was at 200 kW, and the air flow into the room is still at 500 g/s. This is an overventilated case. Then for this case we have 1/10th the area burning,

$$\kappa_s = \frac{11\ \text{g/m}^2\text{-s} \times 1.52\ \text{m}^2 \times 0.037\ \text{m}^2/\text{g}}{0.516\ \text{m}^3/\text{s}} = 1.2\ \text{m}^{-1}$$

and

$$L_v = (1 \text{ to } 4\ \text{m}^3/\text{g}) \times 2.3/1.2\ \text{m}^2/\text{g} = 1.9 \text{ to } 7.7\ \text{m}.$$

This is much clearer smoke, but it will still impair visibility.

Irritating acid gases can have significant effects on people and their ability to navigate through such smoke. Jin[4] reports that for irritating smoke the drop off in visibility is nearly precipitously low at an optical density per path length of about 0. 2 m^{-1}. This is in contrast to smoke (likely without acid gases) shown in Figure 8.6. Also he reports that walking speed can decrease from 1 to 0.5 m/s when walking in clear air to smoke. With irritating smoke, this decrease occurs at an optical density per path length of about 0.17 m^{-1} but at about 0.35 m^{-1} for nonirritating smoke. In general, he reports that people familiar with a building need a visibility of 4 m ($D_o \sim 0.8\ \text{m}^{-1}$) for safe egress, and 13 m ($D_o \sim 0.1\ \text{m}^{-1}$) for those in unfamiliar surroundings. These criteria were based on emotional and physical factors for individuals whom he tested in smoke egress experiments. Factors affecting egress through smoke included irritation to eyes and throat, fear as smoke density increased, and general anxiety as vision reduced, as well as the ability to clearly see.

8.5.5 Heat Effects

Temperature can also cause harm by convective and radiative heat transfer. Two effects are possible: Heat stress is relatively long term; a burn injury is more immediate. If skin reaches 45°C, humans can feel pain. At higher temperatures, damage can occur at increasing tissue depths. Figure 3.10 shows the time response for blister burns due to radiant heating of bare skin. We need at least 4 kW/m^2 to cause such burns in a relatively short time (in contrast to long-term exposure to the sun at $\leq$1 kW/m^2, which can result in a relatively mild skin burn—first degree). Purely convective heat fluxes associated with the threshold heat flux for a blister correspond to a given smoke temperature. This temperature can be estimated from Equation 3.2—the formula for convective heat

transfer. Selecting a heat transfer coefficient of h = 10 W/m²-°C, which approximates a stationary person, gives

$$\dot{q}'' = h(T_{smoke} - T_{skin})$$

$$T_{smoke} = \frac{\dot{q}''}{h} + T_{skin}$$

Solving,

$$= \left(\frac{4 \text{ kW/m}^2}{10 \text{ W/m}^2\text{-°C} \times 10^{-3} \text{ kW/W}} \right) + 45°\text{C}$$

$$= 445°\text{C}.$$

Similarly, the pain threshold temperature for a stationary person is roughly 200°C. Actually, people have been exposed in tests to such high temperatures. The ability to perspire increases their tolerance time. But after long heating, the body core temperature can rise to cause heat stress in spite of perspiration. Heat stress occurs when the core temperature reaches 41°C; normal core temperature is 37°C. At 41°C, consciousness can be affected and further increases can lead to death by hyperthermia. Heat stress occurs when the body can no longer regulate its core temperature. This is roughly described by a balance of energies:

[Rate of energy stored in body] = [Metabolic energy release rate]
+ [Radiative and convective heat rates]
– [Evaporation energy loss rate due to perspiration]
– [Respiration energy loss rate]

If the left-hand side is not zero, we have an imbalance, and the core temperature can go up (or down), indicating the start of heat stress. Table 8.5

TABLE 8.5

Tolerance Times under Heat Stress Conditions

Exposure Temperature, °C	RH, %	Tolerance Time
49	10	~10 days
49	50	~2 hours
49	100	~10 minutes
100	0–100	~10 minutes

Source: Purser, D.A., Toxicity assessment of combustion products, Sect. 8, Chap. 2, in: DiNenno, P.J., ed., *SFPE Handbook of Fire Protection Engineering*, 2nd edn., National Fire Protection Association, Quincy, MA, June 1995.

lists some tolerance limits of people while at rest exposed to high temperatures. Notice that the *relative humidity, RH,* has an effect on the evaporation of perspiration, and therefore affects the tolerance time.

8.6 Summary

Smoke is the flow of products and entrained air away from the fire. Concentrations of combustion products can be computed from their yields. Yield is the fraction of combustion product produced per mass of fuel supplied. These yields depend on the fuel and on the fire condition: flaming conditions of over- or underventilation, smoldering, or heating. The equivalence ratio is a measure of fire ventilation and is crucial in controlling the yields of species and their concentrations in smoke. Concentration is the fraction of the species product in the smoke. The effect of species concentrations over time is known as dose. Dose, the product of concentration and time, can be a direct measure of harm or damage. For narcotic gases, the concept of fractional dose is a model for the combined effects of species. Various criteria are available to quantify the level of harm. A summary of the primary effects to humans from combustion products is listed as follows:

Product	**Effect**
Temperature	Heat stress, burns
CO_2	Increase in respiration
Soot, tars	Visibility
O_2, CO, HCN	Loss of oxygen supply to blood
HCl, HF, HBr	Sensory irritant

Review Questions

1. A smoldering fire occurs in a closed room 40 m^3 in volume. The smoke remains in the room and maintains an average density of 0.9 kg/m^3. It is known for this case that the smoldering is steady at 1 g/s. It produces yield 0.2 g of carbon monoxide per g of fuel smoldered.
   a. Compute the mass of smoke gas in the room.
   b. Compute the mass of CO produced after 1 hour.
   c. Compute the mass (fraction) concentration of CO in the room after 1 hour.

   d. For a person resting, compute the COHb (%) using Equation 8.7 and Table 8.3. Note: The mass fraction (Y) of CO is nearly identical to its volume fraction (X), as CO has a molecular weight of 28 and air is about 29.
   e. In a 40 m^3 room the mass optical density (D_m) of the smoke is 0.33 m^2/g (from Table 8.1). For the 1 g/s smoldering fire, estimate the smoke visibility in the room at 1 hour, assuming smoke is well mixed throughout the room. Use Equation 8.11 and Figure 8.6 for your estimation.
2. Will acetylene produce more soot than propane? Explain the basis of your answer.
3. Compute the equivalence ratio for nylon using Table 8.1 if its burning rate is 10 g/s and the air supply to the fire is 600 g/s. Is it underventilated?

True or False

1. Yield is the same as concentration.
2. An exposure to 50 ppm (50/106) of carbon monoxide can kill you.
3. Visibility through smoke does not depend on lighting. That is why exit signs are not lit.
4. Acid gases, such as hydrogen chloride, can cause corrosion of computer equipment after a fire.
5. Heat stress is usually not a factor to people trapped in a fire but is a serious problem for firefighters.
6. Yield is directly related to concentration.
7. Visibility in smoke is the first hazard to humans in fire.
8. Lethal species can combine to kill you in fire smoke even though each one alone could not.

Activities

1. Examine fire incident statistics and draw from your experience to assess the time span involved in lethal smoldering fires.
2. Why are rats or mice used in smoke toxicity testing to assess the hazard to humans? Do their results directly apply to humans? You will need to research this answer.
3. Examine why CO is a recognized fire hazard to the average person, but HCN is not.

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9

Compartment Fires

Learning Objectives

Upon completion of this chapter, you should be able to

- Explain the processes in the development of fire in a compartment
- Explain flashover, fully developed and ventilation-limited fires in a compartment
- Explain fire-induced flows, neutral plane, and the ventilation factor
- Compute vent flow rates and compartment smoke temperatures

9.1 Introduction

Fire in a compartment involves the containment of smoke and the potential for the fire to spread beyond the compartment. Small fires can transport smoke over great distances. Large fires can be affected by the compartment: enhanced due to thermal feedback (increased heat transfer) and diminished due to oxygen vitiation (decreased air flow to the fire). The motion of smoke and air in these fires is mainly due to buoyant effects as a result of the increased temperatures. Typically, the forced conditioned air supply in a building is secondary to this buoyant flow. We examine these effects and introduce some simplified, but very useful, formulas for assessing smoke temperatures and flow rates. We will also take a close look at the phenomenon of flashover: The transition from an object burning in a room to the fire suddenly growing to it biggest possible size. Smoldering fires for most of this chapter are not deeply addressed. They will be briefly discussed at the end of the chapter.

9.2 Stages of Fire Development

Fire in a compartment is initially unaffected by the compartment conditions. But as the oxygen is reduced in the compartment and the compartment temperature rises, the compartment conditions play a role in the behavior of the fire. The stages of fire in a compartment are depicted in Figure 9.1, in terms of temperature and time. The fire usually develops from a single item (*developing*), then grows rapidly and usually involves others (*flashover*), progresses to the biggest fire the compartment and its ventilation can allow (*fully developed*), and, once extinguished, the process ends with a *cooling stage*.

The stages of a fire in a compartment are described in more detail and are depicted in Figure 9.2. In that figure, the results of computations for that particular room are shown along with sketches of the fire and smoke behavior. A range of realistic furniture properties were used to compute the possible ranges of smoke CO concentrations and visibility. Also, the equivalence ratio is estimated. The results are intended for illustrative purposes and to give quantitative estimates of conditions at that stage of the fire. (The student might try to recompute these fires after reading this chapter to independently confirm their general accuracy.)

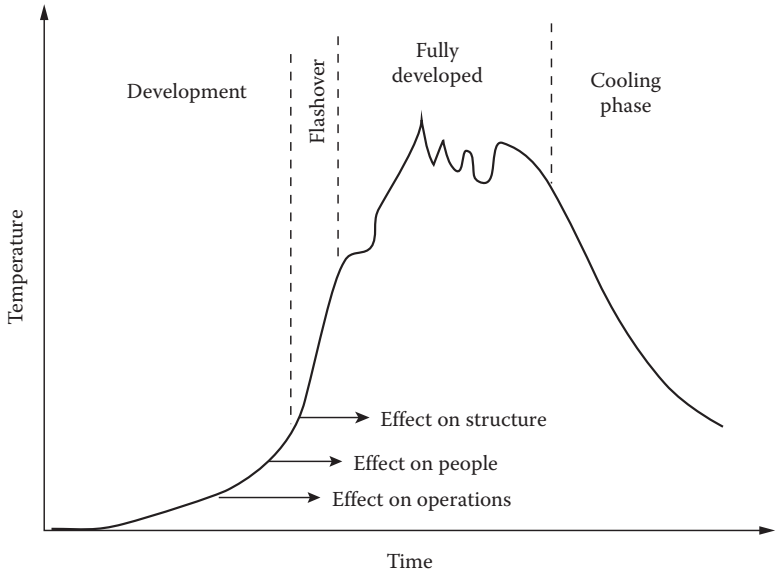


FIGURE 9.1
Stages of fire in a compartment.

9.2.1 Developing Fire

Following ignition, the fire grows on an item and may also involve other items. The oxygen concentration and compartment temperatures are not much different than normal air. The fire behaves as if it is burning in the open air for most of this period (see Figure 9.2a). However, for some fuels, the smoke can have very limited visibility (10 cm) and significant CO content (0.3%). The smoke layer in the room would be above mid-height.

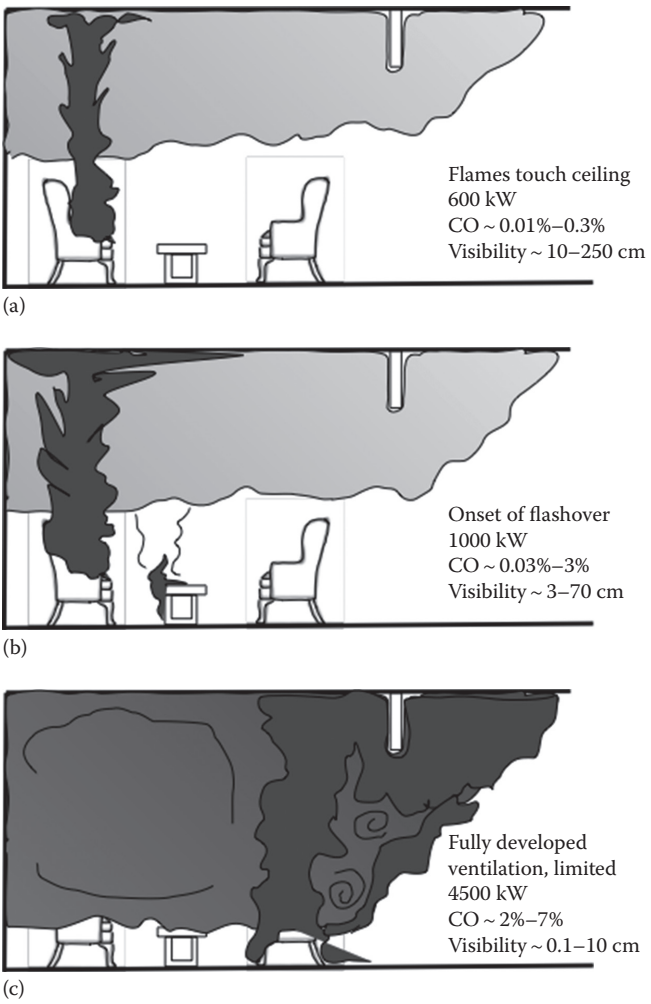


FIGURE 9.2
Typical conditions for furniture items burning in a 10 × 10 × 8 ft high room with a 3.2 × 6.4 ft high doorway. CO is concentration of carbon monoxide. (a) Developing fire, (b) onset of flashover, and (c) fully developed fire.

9.2.2 Flashover

Flashover marks a dramatic increase in fire conditions due to the confinement of a room. Flashover applies to this period of change. It can be caused by several situations:

1. The rapid ignition, burning rate, and flame spread of materials due to increasing heat flux arising from the heated room. This is depicted in Figure 9.2b. This event is commonly called *flashover*. Note that at the onset of flashover, the equivalence ratio is well below 1; the fire is overventilated.
2. The accumulation of fuel-rich gases and their sudden exposure to air with ignition. This is commonly called *backdraft* by the fire service and others but can be regarded as a type of flashover. As a premixed flame can move rapidly through the gas, this event can release a lot of energy in a short time. As a result, the pressure in the compartment can increase, causing a large pulse of flame and possible structural and glass failures.

In the rest of this chapter, we will regard flashover as that described in 1.

There is a beginning and end to *flashover*; it is a transition that can occur over seconds or minutes. It is due to an instability. It is much like an ignition process. In ignition, first there is fuel and air and then there is a flame. In flashover, first there is a small fire and then there is a big fire. For flashover, the instability is caused by the firepower suddenly exceeding the heat loss and energy flow rates from the compartment. This imbalance results in a sharp temperature increase in the smoke of the compartment. Flashover will cause the fire to reach its fully developed state. All of the fuel gases may not be able to burn within the room because the air supply is limited. Flames will occur near the origin or seek out available air supply locations. The flames will not fill the room, but the smoke layer will descend near the floor.

Flashover terminates when all of the oxygen is consumed or when flames cover all of the available fuel in the room. The former state is termed *ventilation-limited*, and latter state is called a *fuel-controlled fire*. Then flashover marks a transition in which the fire development was previously dominated by the fuel materials and subsequently is primarily controlled by the ventilation conditions indicative of the room and building geometry.

9.2.3 Fully Developed

This stage occurs after flashover. If there is sufficient air (fuel controlled), flames fully encompass the room, with the likelihood of flames extending from windows and doors. A fire in a glass tower office building, with full fire on a floor and all the floor-to-ceiling windows broken

(e.g., First Interstate Bank fire, Los Angeles, May 1988), is likely to be fuel controlled. If insufficient air is only available to the room, the fire is ventilation limited. A *ventilation-limited* fire can be defined as one in which the smoke leaving the room has a concentration of 0% oxygen—all of the oxygen is reacted within the room. When the ventilation-limited condition occurs, the production of CO, smoke, and energy are at their highest values. More fuel will be generated by heat in the room than can be burned inside. Its equivalence ratio is greater than or equal to 1. This case is depicted in Figure 9.2c. All of the fuel is involved to its maximum potential. For a ventilation-limited fire, the room's energy release rate is established by the available air supply rate. Most compartments and buildings become ventilation limited at this fully developed stage, as there is always enough fuel in typical furnished rooms compared to ventilation.

Note that in Figure 9.2, typical ranges of values for CO, smoke visibility, and equivalence ratio were computed for various fuels contained in that particular room. The firepower was selected to match the stage of the fire, with a 500°C criterion used for the onset of flashover.

The fully developed state marks the point where the structure becomes vulnerable. Heat flux conditions in the room can reach as high as 270 kW/m^2. This corresponds to a smoke temperature of 1200°C that may occur in large compartment fires. However, Cox[1] reports that in a tunnel fire (Summit tunnel fire, England, December 1984), the incidence of a melted steel rail and fused brick occurred. This is shown in the photograph in Figure 9.3.

FIGURE 9.3
Melted steel rail in the Summit Tunnel fire. (From Cox, G., Private communications, 2010.)

He indicates that fused brickwork could occur at about 1250°C and steel could melt at about 1400°C–1500°C. Both of these effects are shown in the photograph. Such fire conditions would have had extremely high heat fluxes. There has not been sufficient experimentation in large building fires to indicate such heating conditions as the tunnel, but one cannot rule this out.

9.2.4 Cooling Stage

The fire will eventually extinguish as it runs out of fuel in the fully developed stage. The compartment surfaces and objects remain hot. Out-gassing still remains, as fires die to smoldering. The toxic conditions during this period remain hazardous and can be of harm to firefighters. Most significantly the cooling stage is still a factor in heating the structure. This is especially true for steel reinforcing rods in concrete. While the steel rods may not have been heated during the fully developed stage, the thermal penetration in the concrete continues to occur. During the cooling stage, the thermal penetration could reach the vulnerable rods.

9.2.5 Example of Measured Conditions in Room Fire

Let us take a look at the stages of a fire from an experiment reported by Hartzell.[2] This is shown in Figure 9.4. The fire began as smoldering on an upholstered polyurethane-cushioned chair. The measurements were taken at a point indicated in the sketch.

Flashover is perceived at 25.5 minutes. The temperature is 500°F (260°C) at that instant, but reaches about 1000°F (538°C) in less than a minute. At about 27 minutes, the fire reaches the fully developed (and ventilation-limited) stage as the O_2 drops to zero, the CO peaks at 7%, and later, the temperature ultimately reaches 1600°F (870°C). Note that the HCN concentration from the polyurethane foam chair does not increase until well after flashover. Also, the fact that the oxygen drops to zero and remains there clearly shows the fire has used all of the oxygen in the air that entered the room and is ventilation limited.

Because fire development in a room is very important, we shall come back to a more detailed portrayal of it later. Measurements and external observations give some indication of characteristic behavior, but pictures give a more definitive and accurate impression. In the early development of fire research, and this is still relevant today, observations led to concepts and then generalizations on how to model fire and smoke behavior. The processes could be broken into discrete pieces for study. First, we will focus on fire flows and smoke movement.

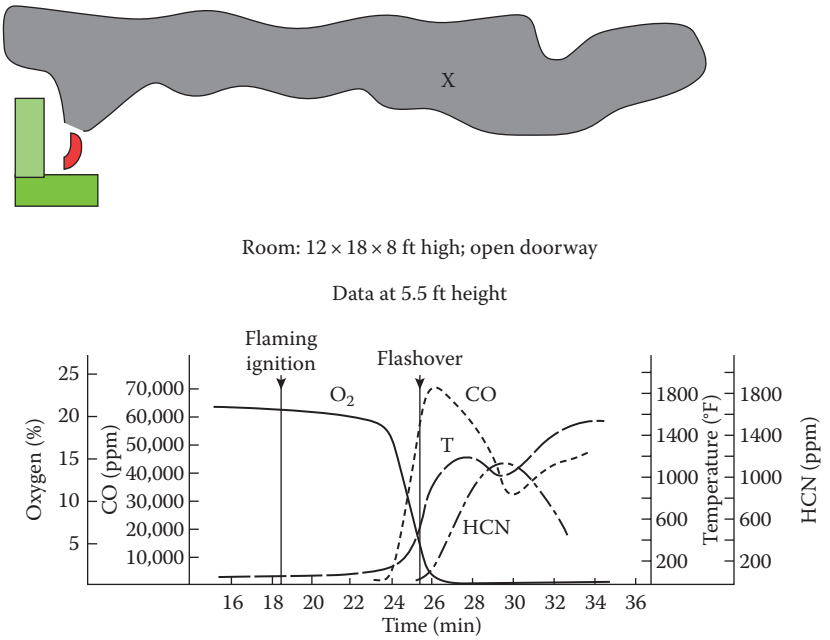


FIGURE 9.4
Furnished room fire initiated by a smoldering upholstered chair. (From Hartzell, G., Combustion products and their effects on life safety, Sect. 3, Chap. 1 in: Cote, A.E. and Linville, J.L., eds., *Fire Protection Handbook*, 17th edn., National Fire Protection Association, Quincy, MA, 1991, pp. 3.3–3.14.)

9.3 Fire-Induced Flows

Flows occur as a result of fire, or in general due to any heat source through buoyancy. Buoyancy causes a pressure difference that results in a velocity. These concepts were presented in Chapter 7. The pressure difference Δp, as related to buoyancy (Δ means a difference in p, i.e., $p_2 - p_1$) is

$$\Delta p = (\rho_a - \rho) g H \tag{9.1}$$

where
ρ_a is the air (cold) density
ρ is the smoke of fire (hot) density
g is the gravitational acceleration, 9.81 m/s^2
H is a vertical height (between positions 1 and 2)

In Chapter 7, we called this pressure difference term relative potential energy per unit volume. Note the unit equivalence:

$$\frac{\text{Energy}}{\text{Volume}} \text{ in } \frac{\text{J}}{\text{m}^3} = \text{Pressure in } \frac{\text{Newton (N)}}{\text{m}^2}$$

One newton (N) is the same as 1 kg-m²/s, and 1 Joule (J) is 1 kg-m³/s or 1 N-m; therefore,

$$1\frac{\text{N}}{\text{m}^2} = 1\frac{\text{kg-m}^2/\text{s}}{\text{m}^2} = 1\frac{\text{kg-m}^3/\text{s}}{\text{m}^3} = 1\frac{\text{J}}{\text{m}^3}.$$

These equal terms are equivalent units of measure although their names are different. A newton and a kilogram are related through *Newton's Second Law of Motion*: Force = Mass × Acceleration.

From equating the potential energy to the kinetic energy as shown in Chapter 7, the resultant velocity due to pressure caused buoyancy is

$$V = \sqrt{\frac{2(\rho_a - \rho)gH}{\rho}}. \tag{9.2}$$

From Equations 9.1 and 9.2, we can obtain approximate formulas to explain the flows associated with fire.

9.3.1 Duct Fan Pressures in Fire

Let us roughly explain the relationship of fire-induced flows compared to fan-generated flows. Such fan flows would occur in air handling systems of a building. Consider two cases as shown in Figure 9.5. The first is pure fan flow over height H in a duct of diameter D. The second is purely buoyant flow where the duct gases are at a higher temperature, T, compared to the air at T_a. The fan would create a pressure difference to just balance the friction effects as given by

$$\Delta p_{Fan} = f\frac{H}{D}\frac{\rho_a V^2}{2} \tag{9.3}$$

where f is a friction factor. (It has no units, dimensionless.)

The buoyant duct would create a pressure difference given by

$$\Delta p_b = \rho_a\left(1 - \frac{T_a}{T}\right)gH \tag{9.4}$$

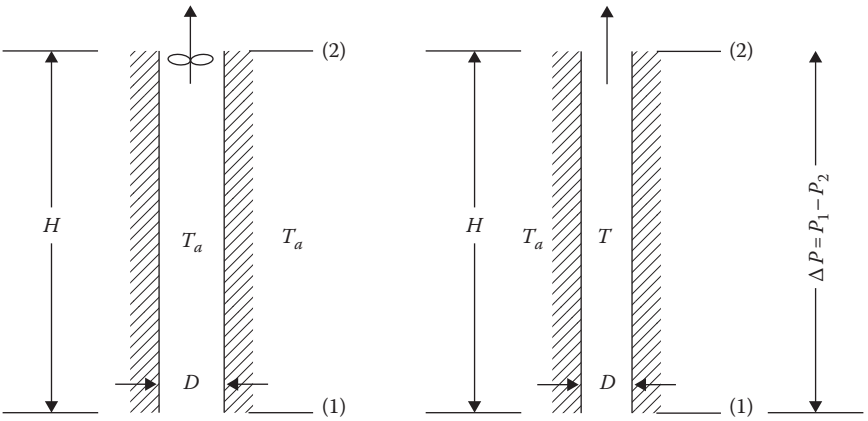


FIGURE 9.5
Ideal fan and buoyant flows in a duct.

This follows from Equation 9.1 where temperature has replaced the density difference.

A representative fan supply flow is 1 m/s in a duct diameter, *D*, of 0.3 m for air at 27°C with a density of 1.2 kg/m^3. The corresponding friction factor for this flow is 0.03. (Some advanced fluid mechanics of pipe flow is needed to obtain the friction factor.) Then, the pressure needed to drive this duct flow is computed from Equation 9.3 as

$$\Delta p_{Fan} = (0.03)\frac{H}{0.3\text{ m}}\frac{1.2\text{ kg/m}^3(1\text{ m/s})^2}{2} = 0.06H\text{ (m) in N/m}^2$$

In comparison, the buoyant pressure generated by smoke at 327°C, from Equation 9.2, is computed as

$$\Delta p_b = 1.2\text{ kg/m}^2\left(1-\frac{27+273\text{K}}{327+273\text{K}}\right)\times 9.81\text{ N/kg}\times H\text{ (m)} = 5.9H\text{ (m) in N/m}^2.$$

The smoke pressure greatly exceeds the fan pressure over the same height, *H*. The fan pressure would approximately equal the buoyancy pressure for duct temperature of 28.5°C, only 1.5°C above outside air. It is clear that, under fire conditions, buoyant flows are likely to dominate fan-generated duct flows. Coupling the fire induced and duct ventilation flows is not simple. But as fire grows, it can be expected that smoke can flow into intake ducts.

9.3.2 Pressure Level Due to Fire

For a moderate value of H, typical of room or building heights, the pressure differences are very small compared to the absolute atmospheric pressure. For example, if $H = 1$ m, $\Delta p_b \sim 5\,\mathrm{N/m^2}$, compared to normal atmospheric pressure of $10^5\,\mathrm{N/m^2}$. (Americans would be familiar with 14.6 psi as normal atmospheric pressure at sea level.) Even for $H = 100$ m, the pressure difference due to buoyancy is small. In general, the pressures due to fire and also due to air handling systems do not cause any significant change in the overall building pressure. Very, very small pressure differences drive these flows, and the overall building pressure does not significantly depart from $10^5\,\mathrm{N/m^2}$. Incidentally, $\mathrm{N/m^2}$ is commonly called Pascal (Pa), as an alternative unit of measure for pressure.

9.4 Compartment Flow Dynamics

Flow dynamics in a compartment fire were revealed through fire experiments in the early 1970s. For a fire on the floor, a plume was discernable, and a hot smoke layer stratified above it. The plume acted as "pump" ingesting air due to entrainment. The smoke stayed on top because it was more buoyant than the cooler air. Buoyant pressures and momentum pushed the flows. Occasionally, some mixing occurred between the smoke and air, especially as the smoke entered or exited the room. All of these effects could be observed in early experiments. Let us examine how smoke flows in a single room, in a corridor, and in a building.

9.4.1 Flow in a Room

Figure 9.6 displays a sequence of sketches that describe the process of fire flows in a room with an opening—a vent near the floor.

At the onset of a fire, its turbulent plume would begin to rise toward the ceiling. As long as its temperature remains higher than that in the room, it will continue to rise until it hits the ceiling. The speed of this rise is relatively fast. This can be appreciated as the velocity is related to $\sqrt{gH}$, indicated by Equation 9.2. For a ceiling at 2 m, this indicates a speed of about 4 m/s at most. Of course temperature and mixing effects will slow this down, but it is relatively fast. Similarly, once the plume hits the ceiling, its momentum is redirected horizontally. Its velocity will slow as mixing occurs and it moves radially through a larger circumference. But this still is relatively fast. This ceiling motion is referred to as a ceiling jet. Research has indicated that its depth varies slightly, but is generally about 1/10th of the distance from the fire source to the ceiling. This depth is significant because detection devices

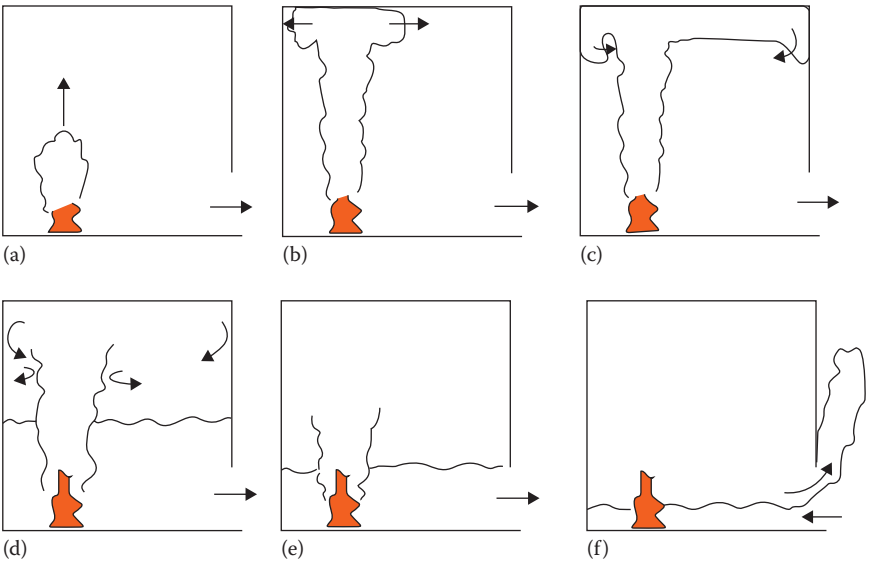


FIGURE 9.6
Sequence of developing fire flows in a room: (a) plume rise, (b) ceiling jet forms, (c) start of layer, (d) layer descends, (e) layer reaches vent, and (f) bidirectional flow.

should be placed within the ceiling jet. The flow below it is relatively tranquil. Detectors should be located within the jet, as they need a reasonable velocity to respond.

Once the ceiling jet hits the confining walls, the momentum of the flow wants to drive it back down, but buoyancy keeps it up. For rooms that are wider than tall, buoyancy always wins. The flow then tries to return to the plume. As only some of it can be re-entrained, it layers in a circulating fashion. This serves to mix the forming layer beneath the jet. The bottom of the hot layer interface is stably stratified with the cooler air below. This interface is fairly sharp and is only blurred by diffusion. The interface oscillates much like shallow ocean waves. It continues to descend.

At the point when the layer reaches the vent, it will fall below it. The smoke layer can continue to drop as the temperature increases. (Cooling would cause the layer to rise.) Up to this point, the pressure of the fire has resulted in flow completely out of the room. But at some point, the layer settles down, and flow must enter the compartment through the lower portion of the vent. By conservation of mass, the outflow cannot continue indefinitely. The resulting bidirectional flow is most common in established compartment fires. For ordinary size open windows or doors, this room developing flow stage occurs relatively quick. Thereafter, the flow is both in and out of the room. As the fire becomes larger, the resultant fully developed room fire can have a layer interface several inches above the floor.

Figure 9.7 gives a more detailed description of the pressure difference and vent flows during the smoke filling process. The energy release by the fire onset causes a pressure rise, and it remains higher than the surrounding air. When the bidirectional flow occurs, the pressure at the lower region of the compartment has now become lower than the surroundings. This sucks the air into the room. The layer position at the vent in bidirectional flow is higher than that in the room, as seen in Figure 9.7c. The vent layer interface is called

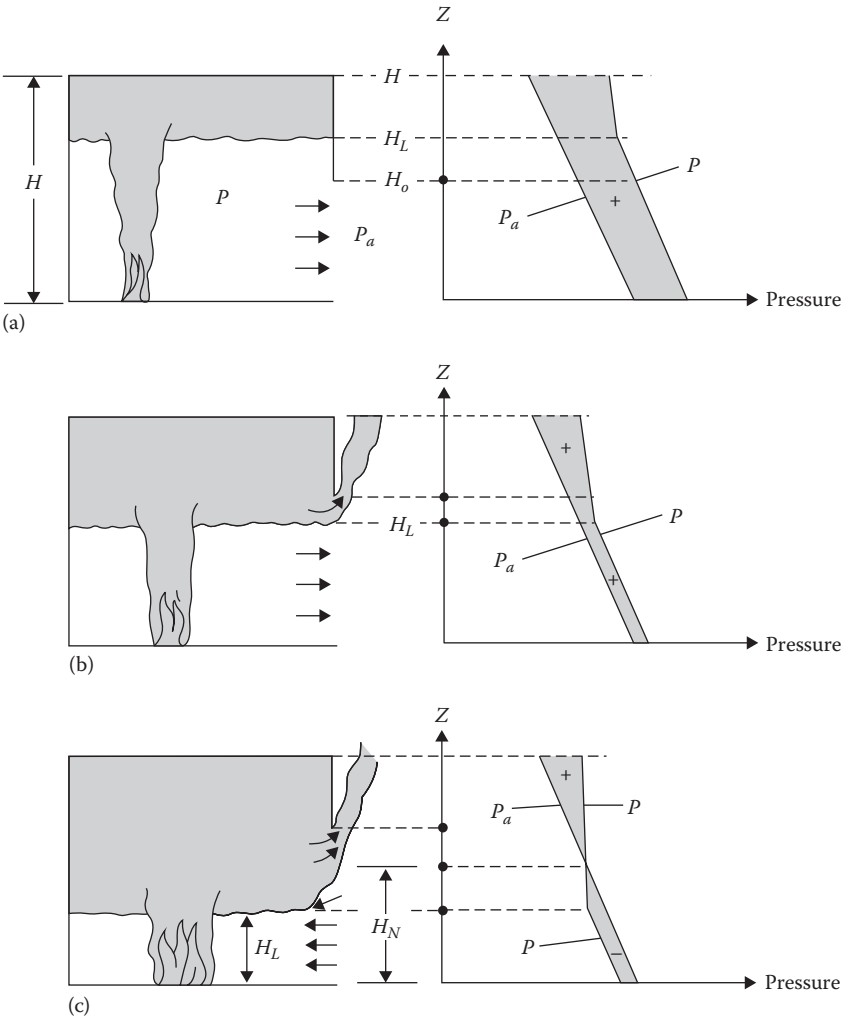


FIGURE 9.7
Flow and pressure dynamics in a room with a vent. (a) Layer descending: cold flow leaves the vent. (b) Hot flow begins to the vent. (c) Layer interface below the vent and cold flow enters from the surroundings.

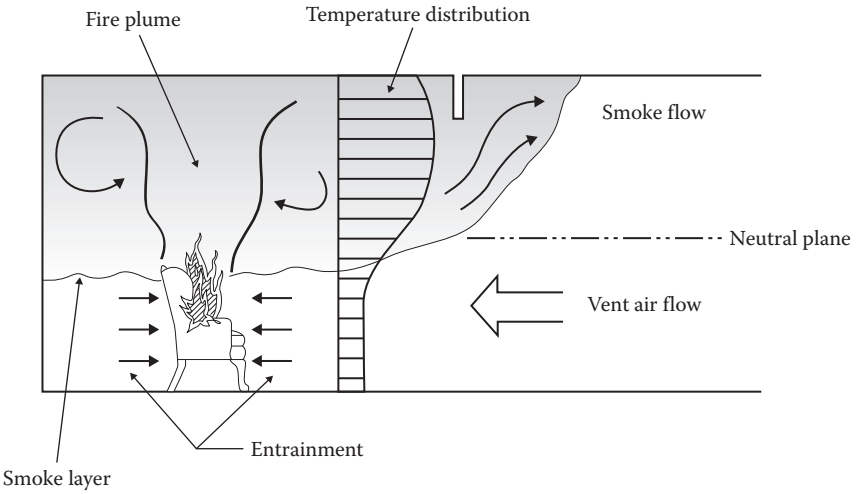


FIGURE 9.8
Fire-induced flows in a room.

the *neutral plane* (H_N). The pressure difference at the neutral plane is zero. This height, for a single door opening, can vary from about 1/2 to 1/3 of the doorway height as the fire gets bigger.

Recirculation within the smoke region in the room drives the temperatures (and concentrations) to become nearly uniform in the vertical direction. Laterally, heat loss can cause decreases in temperature moving away from the fire. But for moderate and small size compartments, the concept of a uniform property smoke layer has emerged as a suitable approximation to the process for describing a room fire. The process is shown qualitatively in Figure 9.8 and quantitatively in Figure 9.9. In the latter, the uniformity is shown for the wall temperatures as well, and the lower layer below the smoke is also fairly uniform. In fact, the wall temperatures exceed the gas temperatures in the lower layer due to radiant heat transfer from the smoke to the lower walls. Notice too that the gas temperatures in the lower layer are above the incoming air (at 25°C) in Figure 9.9 due to mixing as the air enters the vent and descends into the room. This mixing effect can be inferred from Figure 9.7c as air enters above the height of the layer in the room and must entrain some smoke as it plunges to the floor. It forms a floor jet that seeks out the fire. This mixing effect is responsible for bringing vitiated (lower in oxygen) air to the fire. That vitiation will compete with increasing temperatures to control the fire.

9.4.2 Smoke Filling in a Leaky Compartment

The sequence of flow dynamics shown in Figure 9.6 would also apply to a closed room up to (e), with the layer nearly getting to the floor. If the room is perfectly sealed the room pressure would increase continuously and

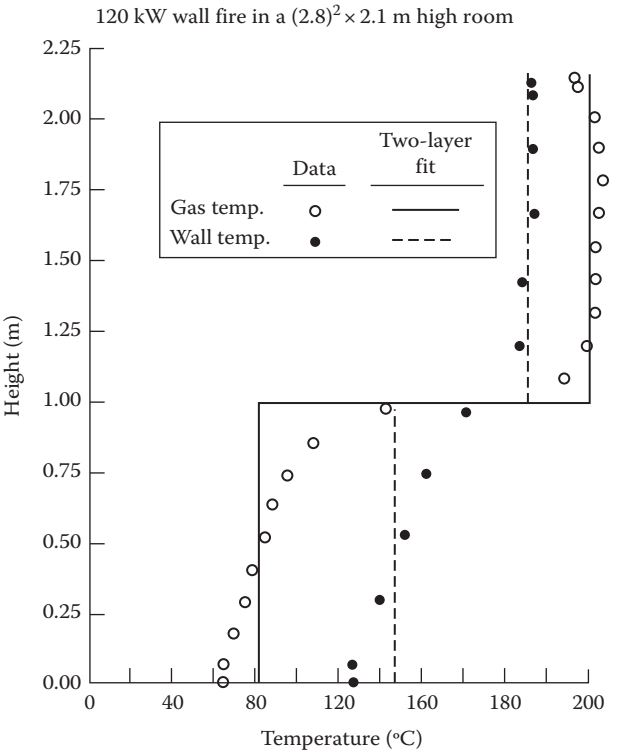


FIGURE 9.9
Room temperatures with a wall vent at a steady state. (After Quintiere, J.G. et al., *Fire Sci. Technol.*, 4(1), 1, 1984.)

significantly as the temperature rises. The pressure would increase by as much as a factor of about three atmospheres. However, unless it is a nuclear reactor containment vessel, or a submarine, this pressure rise will not happen. This is because building structures leak through their membrane, through cracks and gaps, and even designed vents. Figure 9.10 depicts the process for leaks at the ceiling and floor. We will later examine the results of modeling this case in order to estimate the filling time for the layer to descend.

The filling process is the inverse of filling a tub with water. The smoke interface moves down to fill the compartment. All buildings leak; they are not made to be perfectly sealed. For normal buildings, the absolute pressure changes only slightly to cause the appropriate flows within and at the leaks. Essentially normal atmospheric conditions prevail.

During filling and leaking, the pressure within remains slightly positive over the surroundings causing flow out of the room. The layer can descend over the fire, and its decrease in oxygen can affect the fire. If the fire dies due to lack of oxygen, cooling occurs and the pressure within becomes negative

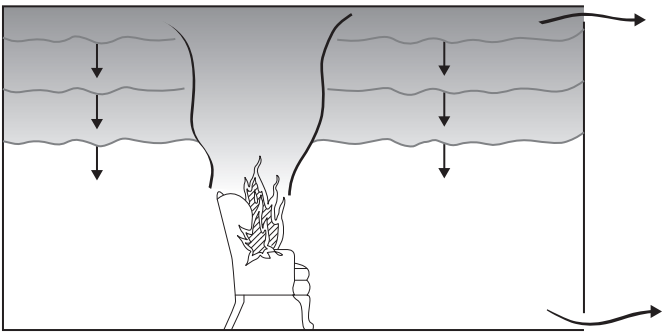


FIGURE 9.10
Smoke filling a leaky space.

with respect to the surroundings, and consequently draws air in. This air can revitalize the fire, and the pressure now goes positive again pushing gases out. The process can be repeated and can appear as if the fire is breathing. Firefighters know this sign and avoid venting such "breathing" enclosures. The room can be filled with unburned fuel, and a sudden rush of air can lead to backdraft.

The filling process can take many minutes to occur. It can be significant in the fire development. For a smoldering fire, the smoldering can persist well after filling, as it requires very little oxygen to maintain the reaction. During this period, it becomes deadly to occupants. In flaming fires, the flames can be extinguished and then lead to smoldering. This may later lead back to flaming if an air supply is found.

In a large space, it may take a long time for filling. I once examined a fire that occurred in a small storage room open on to a large clothing store with a high ceiling. As the store was closed for inventory processing, the workers were unaware of the fire until they smelled it. They smelled it when the smoke layer exited from the storage room, filled the main store, and the layer descended to their noses. A small fire may produce nearly invisible smoke, but odor is surprisingly detected at low levels. I think many have experienced the odor of wood burning at ground level far from a fire, with no sight of smoke.

9.4.3 Smoke Movement in a Building

The dynamics of smoke movement through a building have not been sufficiently studied by experiments; however, we can qualitatively describe the smoke's behavior. Computer models have sought to do this. The *zone modeling* approach views the fire in a room as two uniform layers use the pressure dynamics to predict the flows. Of course, the process is more complicated than the computation associated with Figure 9.5 for a single vertical duct, but computers can keep track of all the pressure differences at the vents in a building computer model. Other computer models try to solve

the basic conservation equations, attempting to model all features of the fire and smoke from first principles. Such a comprehensive computer model is commonly referred to as a CFD model (e.g., stands for computational fluid dynamics, but they do much more). The zone model approach is fast, but the CFD approach has supplanted it as computers have gotten bigger and faster. Here, we will mainly be qualitative and simple in our view of building smoke dynamics.

9.4.3.1 Corridors

Figure 9.11 shows steady flow from a room into a corridor that has an exit vent. A stratified smoke layer whose interface height depends on the size of the exit opening is formed in the corridor. The smaller the exit opening, the lower is the interface (see Figure 1.5). Within the corridor, distinct hot and cold layers form as the smoke stratifies. However, the flow pattern is more complex as shown in Figure 9.11 (or Figure 1.6). Mixing occurs as the flow enters the corridor and the room. A ceiling jet occurs as well as a cold floor jet. In between, the cold and hot layers recirculate. These patterns were determined by flow trace observations as well as by measurements.

If the corridor has no exit vent, it will fill, much like a single compartment, as smoke emerges from a room. If the flow is gradual, we have the process shown in Figure 9.12a, and in the photographs in Figure 9.13a through d. These photographs taken in a closed corridor for a small fire in an adjoining room were visualized with artificial smoke. They clearly show the descent of a smoke layer interface. However, the cold walls introduce a secondary flow. In Figure 9.13d, the smoke begins to dribble down the cooler walls as the layer interface approaches the floor. This is buoyancy in reverse; cooler fluid moves down in this case.

Another possible flow pattern in the corridor is shown in Figure 9.12b. There, a sudden high velocity release of smoke expands into the corridor due to either a rapidly increasing fire or the sudden opening of the room door. The initial momentum, or kinetic energy, of the smoke can cause a wave front propagation that can turn back on itself. Such a flow would fill the corridor by a lateral motion, compared to the more tranquil filling by

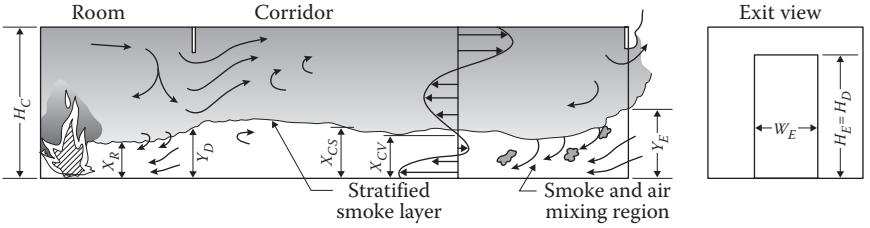
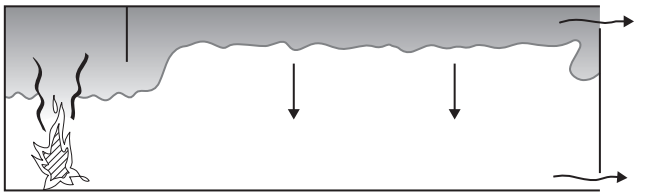
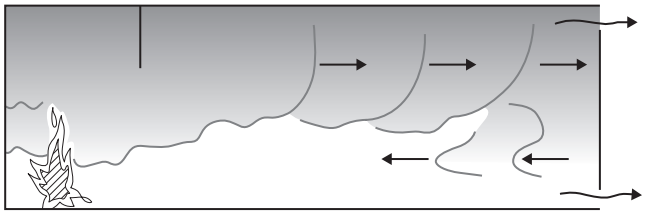


FIGURE 9.11
Fire-induced flows in a room and corridor.

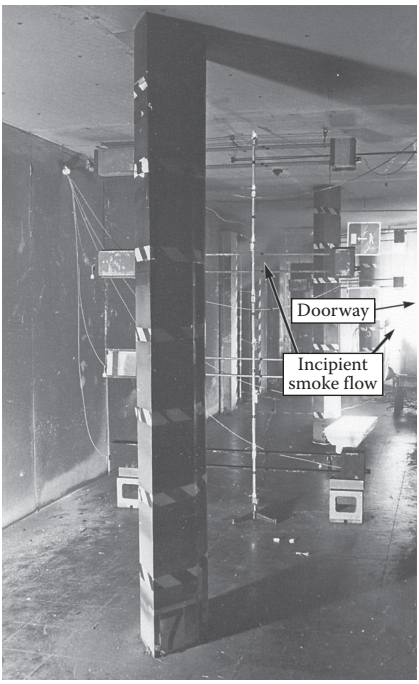


(a)

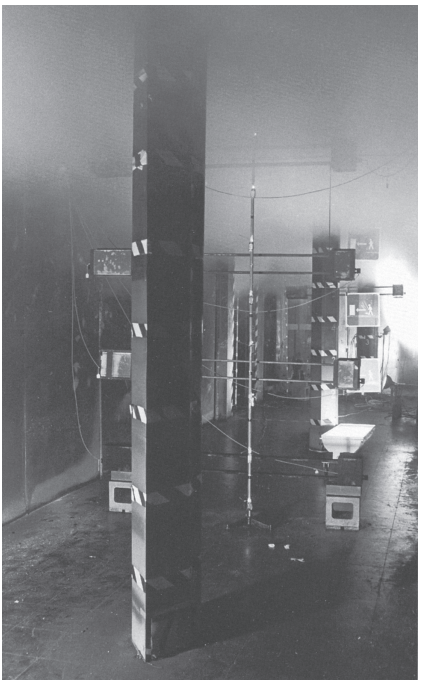


(b)

FIGURE 9.12
Smoke filling a closed corridor (a) slowly and (b) impulsively.



(a)



(b)

FIGURE 9.13
Smoke filling a closed corridor from a room fire on the right. (a) Incipient smoke impinging on the left wall of the corridor. (b) Smoke spreading along the corridor ceiling. (*Continued*)

(c)

(d)

FIGURE 9.13 (*Continued*)
Smoke filling a closed corridor from a room fire on the right. (c) Smoke layer at mid-height and descending. (d) Smoke layer descending near floor.

layering. The velocity of this front can be estimated by Equation 9.2, with H given as the corridor height. It could be several meters per second.

I once investigated a high-rise fire that had two interconnecting floors of plan office space occupied by a law firm. The floors were connected by an open stairway, but the elevator lobby entrances were locked and monitored by infrared security stations. The offices were unoccupied by people at the time of the fire. When a fire in an exterior perimeter office broke the windows and went to flashover, its wood door to the plan office space failed at the hinges and fell. The momentum of the smoke from the room carried it along the top upper floor and then down the internal stairway. The infrared motion detectors at the elevator lobbies alarmed at about 30 seconds apart indicating this smoke flow occurred.

9.4.3.2 Vertical Shafts

Flow up a tall shaft, such as an elevator conduit, would initially be plume-like until the walls intercept the plume. This flow is shown in Figure 9.14. After interception, a complex mixing process occurs that carries the smoke upward. Once the shaft is filled with hot smoke, it can act like any other chimney if it is vented at the top and bottom. The subsequent flow in the

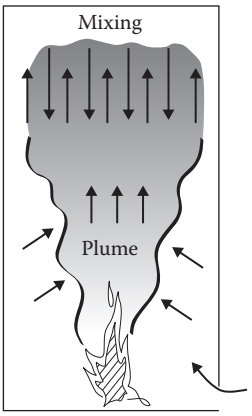


FIGURE 9.14
Smoke filling a shaft.

shaft depends on vents and leakage in the shaft. With no venting, the leakage could bring air in and smoke out.

Figure 9.15 shows the flow processes in a building having been filled with smoke. The hot shaft carries the smoke to the upper floors, and smoke leaks out above the neutral plane of the building. The *neutral plane* is where the pressure difference between inside and outside of the building is zero. Its location will depend on the venting from the building. For the simple case of a closed building of height H_B with leakage through the skin, and at a uniform inside temperature (T) compared to outside (T_a), the neutral plane (H_N) is found by

$$\frac{H_N}{H_B} = \frac{1}{1+(T/T_a)^{1/3}} \tag{9.5}$$

This would be the case of a heated building on a cold day. For summer conditions with a warmer outside temperature, and conditioned cool air inside, the flow would enter the building through the top skin and exit below the neutral plane. The location of this neutral plane would follow Equation 9.5 with the temperature ratio reversed, T_a/T. The summer and winter conditions of a tall building present a *stack effect* that causes flows even with no fire. The neutral plane would be about half the building's height for such temperature conditions.

This *stack effect* flow pattern due to the air heating and cooling conditions of a building would mitigate any fire flows. The fire would introduce a more complex flow. The fire floor would have its own neutral plane when it dominates the building's stack effect, as shown in Figure 9.15. Also wind can affect the building smoke dynamics, particularly by altering the pressures around

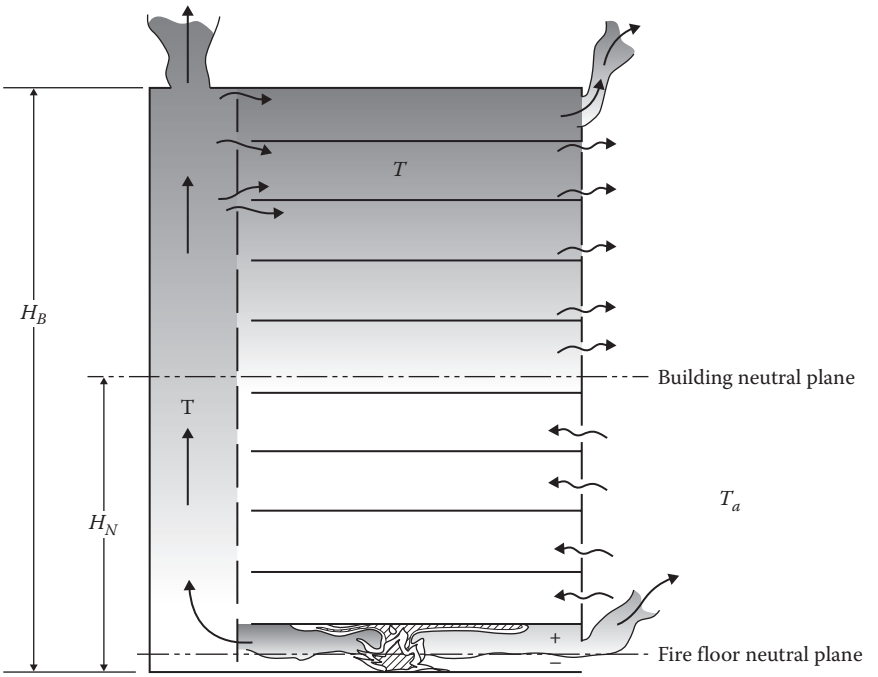


FIGURE 9.15
Simplified dynamics of smoke filling a building.

the building. An early small fire in an air-conditioned building in the summer could experience downward motion of smoke in cool shafts and leakage of smoke below the fire floor. Fire flows in tall buildings can be complex. It is surprising that we do not use the available smoke detectors as an intrinsic diagnostic tool in a high-rise building fire.

9.5 Single Room Fire Analyses

Let us consider how to make some quantitative fire estimates for a single room. We will consider a room with leakage and one with a vent. We will show how to estimate smoke filling time and the smoke flow rate through the vent and its temperature. We will not derive these formulas, as they can be found in the references. But we will try to show how the variables that control the results enter the formulas and how to use the formulas through graphs.

9.5.1 Smoke Filling

Zukoski et al.[4] were first to formulate a prediction for the smoke layer descent. Figure 9.7 gives the notation with the layer height as H_L and the height of the room as H. The fire is considered on the floor in the presentation, and the effect of a raised fire can be considered too.[4] As the Zukoski dimensionless number Q^* was introduced in Chapter 7, it is significant to present the basic filling formula in these terms. For the simplest case of only a ceiling vent, the equation gives

$$\frac{H_L}{H} = \left(1 + \frac{2}{3}\alpha Q^{*1/3}\,\tau\right)^{-3/2}.$$

The formula is just for presentation purposes. Q^* here is based on the height, not the diameter as in Chapter 7; the term τ is a dimensionless filling time with α as an empirical constant varying from about 0.19 to 0.21 depending on entrainment.

In a more practical form for the equation, we write the time for filling as

$$t_{fill}\,(\mathrm{s}) = 24\left(\left(\frac{H}{H_L}\right)^{2/3} - 1\right)\frac{S\,(\mathrm{m}^2)}{H\,(\mathrm{m})^{2/3}\dot{Q}\,(\mathrm{kW})^{1/3}} \tag{9.6}$$

where

$\dot{Q}$ is the firepower
S is the surface area of the room floor

(In the development of Equation 9.6, the radiation loss fraction from the fire was taken as 0.3, and its variation will not introduce any large differences.) The results are meant to be approximate, and other leakage configurations at just the bottom or distributed over the height of the room will change the results. But this formula will give in general a good order of magnitude estimate with about 50% accuracy at worst. Also the formula is for a fixed firepower, not a growing fire that is more common. To account for different fire sizes, Figure 9.16 is introduced to facilitate estimations from Equation 9.6. The times are computed for two smoke layer interface depth ratios (H_L/H) for a 50 m^2 room floor area. The depth ratio of 0.5 is indicative of filling to a vent such as an open door or window. The depth of 0.2 is getting close to the floor, and due to the cold wall downward flows, the smoke might be considered effectively very near the floor. The very small fire powers are indicative of smoldering fires (less than 1 kW), and fill times to near the floor are more than 10 minutes. In contrast, a fire power of over 100 kW drops the layer to a vent location in about a minute or less for the room height of 3 m.

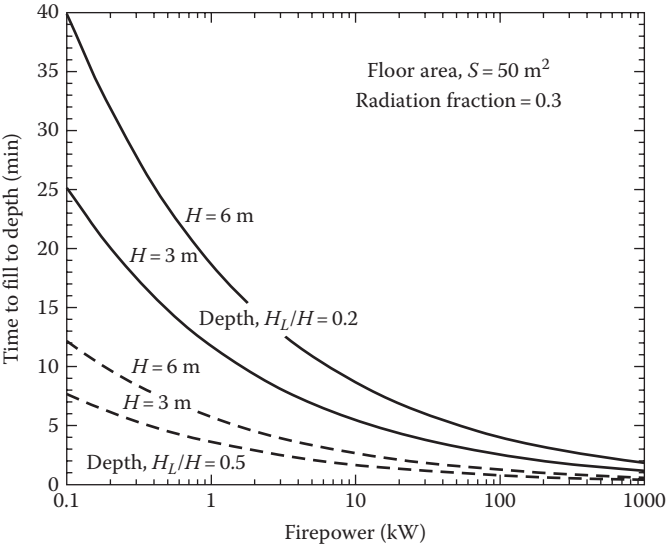


FIGURE 9.16
Time for smoke filling to various depth in a room heights 3 and 6 m with a floor area of 50 m^2.

9.5.2 Smoldering Fire in a Closed Space

Compared to flaming fire, relatively few studies appear for smoldering. Sometime ago experiments by Birky[5] were analyzed. An upholstered chair smoldered in a small closed room. Photographs and measurements of carbon monoxide revealed the nature of the process. Figure 9.17 shows the smoke dynamics of the smoldering upholstered chair fire in the closed room 8.8 m × 2.4 m high. The smoldering was initiated by a simulated lit cigarette. The photographs show that the smoke layer interface is not as sharp as would occur in flaming fires. This is so because the slower process gives more time for diffusion and secondary wall flows to occur.

Figure 9.18 shows the corresponding CO concentration as the smoke layer descends. The smoke reaches the floor in 67 minutes. The CO concentration at that time is about 1%. The accumulation of CO, or dose to a person exposed, is the area under the CO–time curve. By the time of complete filling, the dose is likely to be incapacitating. This can be estimated more precisely by referring to Chapter 8. The theory of filling was used to compute the solid line curves in Figure 9.18. Oxygen remains high (typically > 16%) and temperature increases are small (<50°C) in these conditions. Smoldering can occur in upholstered chairs with cotton or flexible polyurethane cushions with yields of CO at about 0.1–0.2.

Figure 9.19 shows theoretical results for this same chair fire in 2.4 m high room for a range of floor areas. The CO concentrations were computed, and the time to reach an incapacitation level (estimated as CO (%) × time = 4.5%-min)

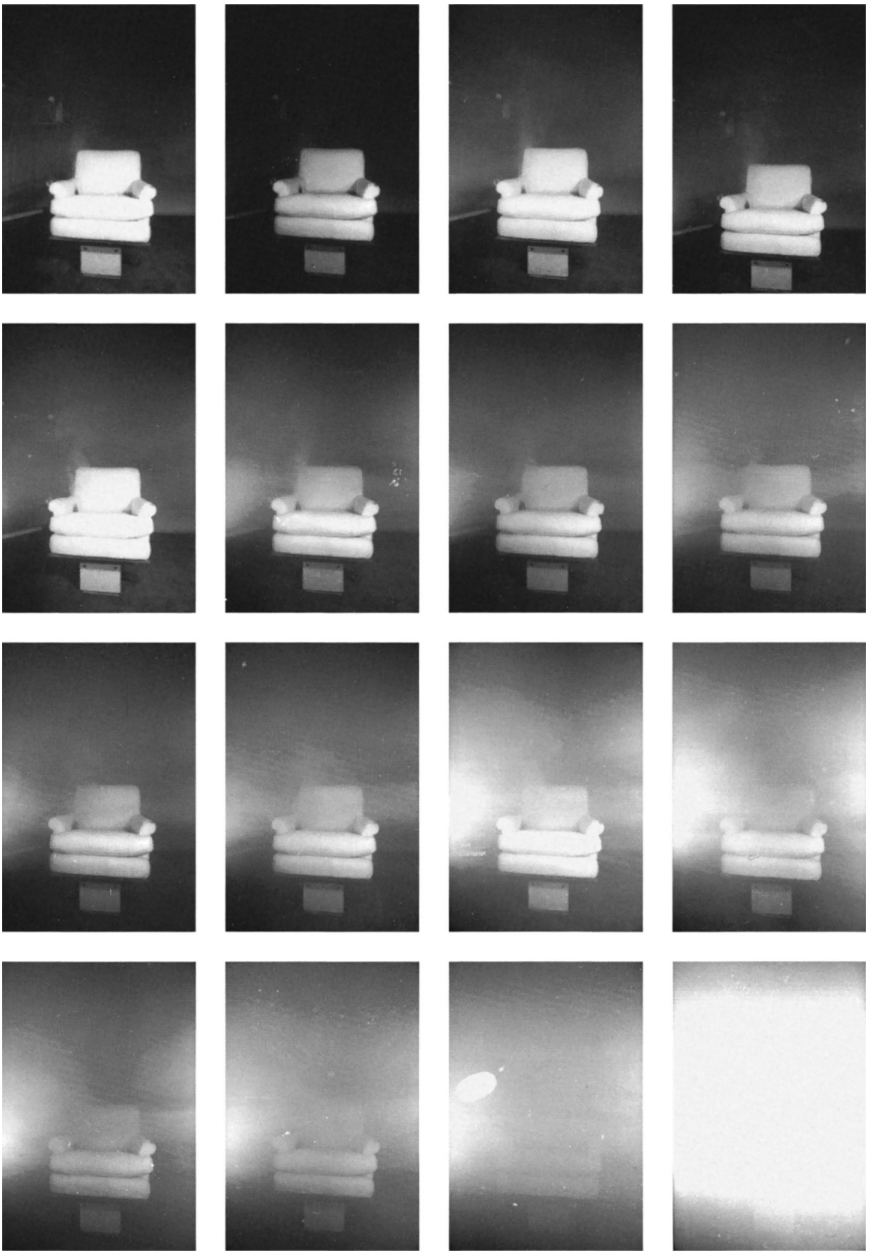


FIGURE 9.17
Photo sequence of smoldering chair smoke filling a closed room.

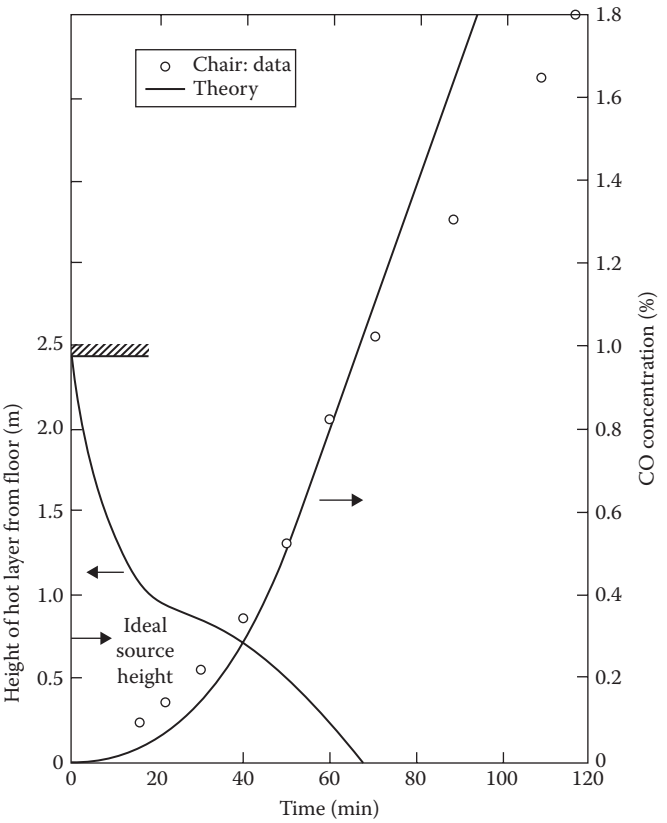


FIGURE 9.18
Dynamics of smoldering chair fire in a closed room. (After Quintiere, J.G. et al., *Fire Mater.*, 6(3 and 4), 99, 1982.)

is indicated as t^* (and "*" on the curves). The smoldering source on the chair was placed at 0.4 m above the floor; the CO is sensed at a height of 1.2 m, representative of a sitting position. The time for the smoke layer to first reach 1.2 m above the floor is indicated by t_o in Figure 9.19. For residential room size spaces, incapacitation occurs within 1 hour, but for house size spaces, it may take up to 2 hours. These times are consistent with actual smoldering fire incident data. But often the fire will not remain as smoldering, and a transition to flaming can occur in similar times as those indicated for incapacitation. This transition to flaming can accelerate the increase in CO content of the smoke. Such a transition is not currently predictable; it strongly depends on aeration and flow velocity at the smolder region. Both processes, flaming and continued smoldering, can be deadly to occupants in these times of 1–2 hours. Smolder continuously yields low levels of CO over a long period, but a ventilation-limited fire can lead to CO concentrations of 2%–7% in a short time following flashover. The latter can cause incapacitation in less than 2 minutes.

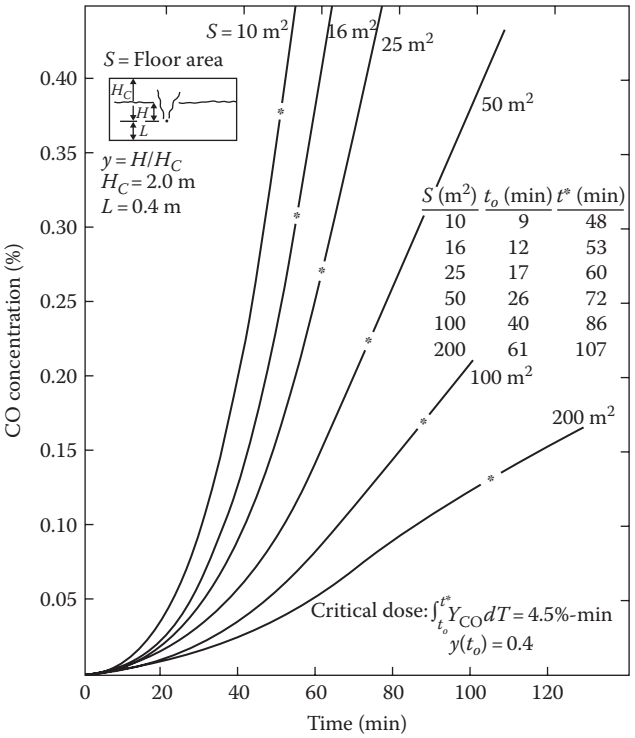


FIGURE 9.19
The increase of carbon monoxide for smoldering chair fire in rooms of different sizes. (After Quintiere, J.G. et al., *Fire Mater.*, 6(3 and 4), 99, 1982.)

9.5.3 Vent Flows

We have seen in Figure 9.7c that the pressure difference caused by the difference in smoke and air temperatures drives the flow across the vent. The rate of smoke flow out is nearly equal to the rate of air flow in. The difference is the small amount of fuel gases produced in the room. The exact mass flow rate depends on the temperature difference and the size of the vent opening. For a vent of height H_o and cross-sectional area of A_o, the maximum air flow rate, $\dot{m}_{a,\max}$, is given by

$$\dot{m}_{a,\max}\,(\mathrm{kg/s}) = 0.52 A_o\,(\mathrm{m}^2)\sqrt{H_o\,(\mathrm{m})} \tag{9.7}$$

where
A_o is in square meters
H_o is in meters

This formula was first determined by Kunio Kawagoe, a noted Japanese fire research pioneer. For large fires or small vents, Equation 9.6 is a good approximation in estimating the air supply rate. Incidentally, $A_o\sqrt{H_o}$ is called the *ventilation factor* because it is the principal variable controlling flow rate. A_o accounts for the flow area and the $\sqrt{H_o}$ accounts for the velocity as described by Equation 9.2.

Large vents and temperatures well below 800°C have lower flow rates than this maximum. The relationship with actual flow rate data for crib fires in a room is illustrated in Figure 9.20.[6] The theoretical maximum, Equation 9.7, places an upper bound on these door flow data. Recently, a formula was developed for the entire range of flow conditions.[7] It has been shown accurate with data within ±20%. It depends on the location and type of fire, the temperature, and the nature of the vent—window

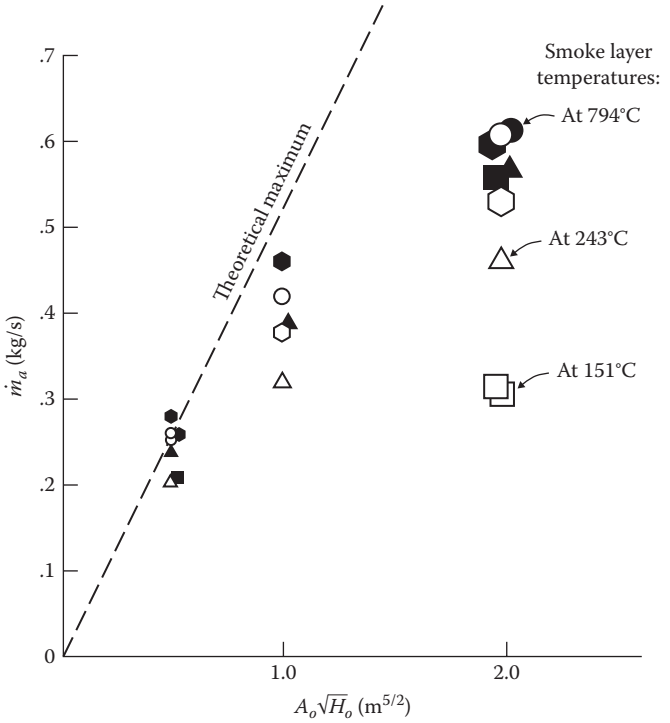


FIGURE 9.20
Airflow rates through door openings for wood and plastic crib fires. (From Quintiere, J.G. and McCaffrey, B.J., The burning of wood and plastic cribs in an enclosure, Vol. I, NBSIR 80-2054, National Bureau of Standards, Gaithersburg, MD, September 1980, p. 49.)

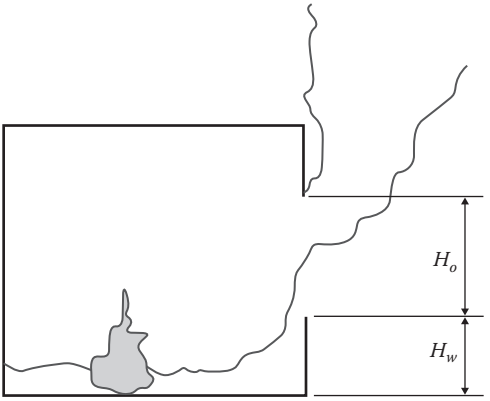


FIGURE 9.21
Notation for mass flow rate through a window or door, Equation 9.8.

or door. It applies to Figure 9.21 where the notation in the formula is described and is given as

$$\frac{\dot{m}}{A_o\sqrt{H_o}} = 0.52\frac{\text{kg/s}}{\text{m}^{5/2}}e^{-Cy}\left[1+0.6(1+(Cy)^2)(1-e^{-3H_w/H_o})^2\right] \tag{9.8}$$

where

$$y = \left(\frac{W_o}{H_o}\right)^{2/3}\left(\frac{T_a}{T-T_a}\right)^{1/2}$$

C = 0.55 for a centered floor pool fire, 0.85 near a wall, 1 in a corner or for a crib.

Let us consider a graphical representation of a special case for this formula. Take W_o/H_o as 0.5, H_w/H_o as 0 for a door, and 0.5 for a window, and consider a centered pool fire with C = 0.55. For normal surrounding air temperature, T_a = 293 K, and representing $T - T_a$ as ΔT, this special case is given as

$$\frac{\dot{m}}{A_o\sqrt{H_o}} = 0.52\frac{\text{kg/s}}{\text{m}^{5/2}}e^{-\left(\frac{5.93}{\Delta T^{1/2}}\right)}$$

$$\times\left[1+0.6\left(1+\left(\frac{5.93}{\Delta T^{1/2}}\right)^2\right)\times(0 \text{ for a door, and } 0.604 \text{ for the window})\right].$$

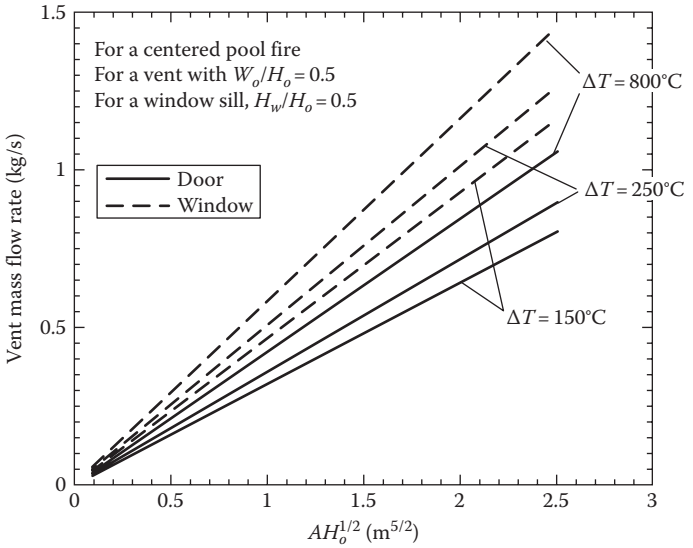


FIGURE 9.22
Flow rates through door and window vents for a centered pool fire.

It is plotted in Figure 9.22. Notice that for the same dimensional of height and width, the window vent gives a higher flow rate because the smoke layer is at or below the sill. The pressure difference is higher for the window than the door. If the constant for a crib fire were used, the flow would be less than that of a pool fire on the floor due to the differences in entrainment.

Change the factor *C* in Equation 9.8 to 1 for a crib and a use doorway and see how well the data of Figure 9.20 match.

These formulae give an estimate of the mass flow of air into a window or door vent. Multiple doors and windows, and ceiling or floor vent will complicate the process. These can only be appropriately computed by a more involved analysis. For wall vents and a fire on the floor, the additivity of the flows through each vent is a reasonable assumption. For more complex vent configurations, a simple formula computation can be prohibited.

In particular, the case of single roof vent without any additional vent below or a singular ground opening to an underground basement fire cannot be predicted by the earlier formulas. The flow is more complicated and not driven solely by pressure differences. In these "ceiling" vent cases, the flow can be bidirectional or oscillatory. A single ceiling vent would have a much less flow rate than a wall vent of the same size. It can be as small as 1/10th the same size wall vent.

These fire-induced flows provide the air supply to the fire. The flow rate has an upper limit for wall vents by Equation 9.7, and a single ceiling vent of the same size would be much smaller. While the flow of air and smoke is governed by pressure differences, the fire supplies fuel gases by heat transfer, and this process is independent of the air supply. When there is not enough air, the fire becomes ventilation limited. A ceiling vent is representative of the flow that would supply air to a basement or ship fire. Such limited air supply can make these fires burn longer and more incompletely and toxic. In such cases of low air supply, the burning rate within the fire space is controlled by the air flow rate. Essentially, all the oxygen in the air is used, and excess fuel escapes in the smoke. The volume of flames inside is limited by air flow, and so then too is the heat transfer to produce the fuel gases. Therefore, the burning rate within and the fuel gas production rate is limited by the air flow.

Beyond the flame volume, the temperature of the smoke controls the heat transfer within the compartment. Heat transfer is significant in driving the fire growth rate. Smoke temperature will depend on air supply and how much fuel can burn. Let us examine predictive formulae for the smoke temperature.

9.5.4 Smoke Temperature

Figures 9.6 through 9.9 depict the smoke layer region in a room fire. This region is extensive in the room especially compared to the volume associated with the flame and buoyant plume regions. The smoke layer is analogous to the bath water filling at least half the bathtub with equal in and out flows of water. So the level stays fixed, but with some wavy motion. As with the bath water temperature, its recirculation from the inflow would allow it to achieve a fairly uniform value. Similarly, we would expect the temperature of the smoke layer, not counting the plume region, to become fairly uniform. This is substantiated in the vertical direction of Figure 9.9, and the nature of the lateral mixing demonstrates the tendency toward a uniform smoke layer temperatures. Indeed early fire research into compartment fires showed this to be a reasonable representation of the smoke layer. Of course, it can vary within the room, but away from the flames, it can be reasonably uniform. Radiant heat tends to promote uniformity and convective heat loss tends to drop the temperature as the smoke moves from the fire to the exit.

Therefore, a first approximation to the temperature in a room fire is to consider the smoke temperature. The smoke temperature will be affected by the size of the fire, $\dot{Q}$, and the ventilations factor, $A_o\sqrt{H_o}$. The larger the fire $\dot{Q}$ and the smaller the vent (or more precisely the ventilation factor), the higher we expect the smoke temperature. In addition, cooling through the enclosing compartment construction area (A) will affect the smoke temperature.

It is not surprising an approximate formula for the smoke temperature will involve these variables. The temperature rise above the surrounding incoming air is given as $\Delta T = T - T_a$:

$$\Delta T\ (°\text{C}) = C_T \left(\frac{\dot{Q}^2}{(hA)(A_o\sqrt{H_o})} \right)^{1/3} \tag{9.9}$$

where

C_T is 6.85 for centered fires, about 12.4 for a corner fire, and about 16.5 for room linings

A_o is in square meters

H_o is in meters

A is the interior surface area in square meters

h is a heat loss coefficient taken as the larger of

$$h = \text{Maximum of} \left(\sqrt{\frac{k\rho c}{t}} \text{ or } \frac{k}{l} \right) \text{in } \frac{(\text{kW})}{(\text{m}^2\text{-}°\text{C})}$$

where

$k\rho c$ is the interior construction *thermal inertia* $(\text{kW}/(\text{m}^2\text{-}°\text{C}))^2\text{-s}$

k is thermal conductivity

l is the interior construction thickness in meters

t is time in seconds

Table 9.1 gives typical values of k and $k\rho c$ for common construction materials.

As seen the temperature rise depends on fire size, ventilation factor, and heat transfer to the compartment construction. As with plume temperature, this equation also could have been put in dimensionless terms using a Q^* based on the ventilation factor. It is sometimes given in those terms, but here

TABLE 9.1

Typical Construction Thermal Properties

	Thermal Inertia, $k\rho c$ $((\text{kW/m}^2\text{-K})^2\text{-s})$	**Thermal Conductivity, k (W/m-K)**
Insulation board	0.09	0.041
Wood	0.30	0.15
Gypsum board	0.60	0.5
Concrete	2.0	1
Steel	150	50

it is given in specific dimensions to facilitate its use. The equation gives the average temperature of the smoke exiting the compartment. It was generally based on the exit maximum temperature in developing its correlations. Higher point-wise temperatures will occur in the room. The equation was developed for room-centered fires by analyzing many different tests. Others have investigated other fire configurations, such as a fire in a corner, or with wall and ceiling linings burning.[8] The differences among the configurations are due to differences in the rate of entrainment into the fire configurations. Also the equation can be used for multiple wall vents by summing the $A_o\sqrt{H_o}$ values and can be used for different construction materials by summing the hA values for the various wall, ceiling, and floor elements.

Example 9.1:

Consider a room 4 × 4 × 3 m high with a simple vent 1 × 2 m high. The construction is essentially gypsum plaster with properties given in Table 9.1. The fire is constant at 500 kW. Assume the gypsum is very thick. Compute the temperature rise of the smoke at 100 s.

$$A_o = 2 \text{ m}^2$$

$$A_o\sqrt{H_o} = 2\sqrt{2} \text{ m}^{5/2}$$

$$A = 2(4\times 4) + 4(4\times 3) - 2 = 78 \text{ m}^2$$

$$h = \sqrt{\frac{k\rho c}{t}} = \sqrt{\frac{0.60}{100}} = 0.0775 \text{ kW/m}^2\text{-K}$$

Therefore, from Equation 9.9,

$$\Delta T = 6.85\left[\frac{500^2}{(0.0775)(78)(2\sqrt{2})}\right]^{1/3} = 167°\text{C}$$

There is a restriction on the use of Equation 9.9 in that there must be sufficient air for its use. When there is insufficient air the firepower must be computed by burning all the oxygen in the incoming air flow rate. We will come back to this shortly.

9.5.5 Flashover

In Section 9.2.2, flashover was defined as a sudden increase in the firepower, and it has a beginning and end. Many have used temperature in the compartment as an indicator of the onset of flashover. Commonly a temperature rise of 500°C is a selected criterion. Radiation from the smoke layer is the principal driver of fire growth in a room. The blackbody radiant heat flux arising from this temperature (500°C + 25°C air temperature) is 23 kW/m^2

(from σT^4). At this heating level, we can expect some items to ignite, flame spread to increase, and burning rate to be enhanced. The onset of this increase in fire growth (*trifecta*) could be perceived as the onset of flashover. Thus, if we use a ΔT = 500°C to indicate flashover potential, Equation 9.9 would give us the conditions required for flashover to start. Substituting and solving for $\dot{Q}$

$$\dot{Q}_{FO} = \left[\frac{(500)}{6.85}\right]^{3/2} \left[(hA)(A_o\sqrt{H_o})\right]^{1/2} \text{ for a room-centered fire.} \qquad (9.10)$$

The coefficient is 624 with units as specified in Equation 9.9.

Example 9.2:

For the room of Example 9.1, presuming flashover at near 100 seconds, we can estimate the firepower needed to cause flashover:

$$Q_{FO} = 624\left[(0.0775)(78)(2\sqrt{2})\right]^{1/2} = 2580\,\text{kW}.$$

If the actual fire is constant at 500 kW, it is insufficient to trigger flashover, assuming other combustible items are available for fire growth.

Here, we have arbitrarily used a benchmark of temperature rise of 500°C to indicate the onset of flashover. Flashover is caused by the sudden temperature rise and its associated heat flux influence on fire growth. This fire growth can occur due to an increase in burning rate, remote ignitions, and/or by increasing flame spread. These different growth processes have different trigger points. It is not uncommon in upward flame spread to launch rapid spread with a smoke temperature rise of only 300°C. These differences in temperature at flashover are due to the nature of the growth processes that cause the instability of flashover. So a temperature criterion for flashover is only an approximation. Shortly, we will investigate the anatomy of fire growth through flashover, and some of the issues in this discussion may be more appreciated.

9.5.6 Ventilation-Limited Fires

The criterion for a *ventilation-limited fire* is that in the exiting smoke all the oxygen has been consumed within the room and its concentration is zero. A measure of this is the equivalence ratio, Φ. When Φ is 1, under complete combustion all of the fuel and oxygen in the air have been ideally consumed. As we do not have ideal complete combustion in fire, the equivalence ratio criterion is an approximate indicator. But as Φ increases past 1, the oxygen concentration in fires drops to near zero.

Some quantitative estimates can be made to assess when a room fire becomes ventilation limited. We know how to compute the maximum air flow rate, which is valid for small vents or large fires. From Example 9.1, we can compute this upper limit from Equation 9.7,

$$\dot{m}_{a,\max} = 0.52(2\sqrt{2}) = 1.47\ \text{kg/s}.$$

Almost all common fuels produce approximately 3 kJ/g of air (or 13 kJ/g of oxygen consumed in the air). If all the oxygen is consumed we have a ventilation-limited fire and the maximum possible energy release rate within the room is then

$$\dot{Q}_{\max} = \dot{m}_{a,\max}(\text{kg/s}) \times 3000\ \text{kJ/kg}. \tag{9.11}$$

Following on the previous example, this is

$$\dot{Q}_{\max} = 1.47 \times 3000 = 4,412\ \text{kW or } 4.4\ \text{MW}.$$

We see that this energy release is greater than the value to initiate flashover. This difference between flashover and ventilation-limited energy is true in general for compartment fires. Typically flashover occurs and then the fire has the potential to become ventilation limited. However, for a small vent, the fire may never grow to a flashover state. A ventilation-limited fire could be sustained, or the fire could self-extinguish. This form of fire can lead to a *backdraft* if the ventilation is abruptly increased.

Example 9.3

It is useful to consider the combination of Equations 9.9 through 9.11. Let us take a special case for illustration. Consider a room 7 × 7 m and 2.4 m in height. Let it be lined with gypsum board, and select, for illustration, a time of 6 minutes in the fire. Then, $hA = (0.60/360)^{1/2} \times 165.2 = 6.74$ kW/K. For this value, Equation 9.9 can give the firepower for a given ventilation factor. The results are plotted in Figure 9.23. This graph shows lines of constant temperature rise, with one as the flashover benchmark. The dashed line gives the maximum possible firepower due to the fire becoming ventilation limited as computed from Equation 9.11. A typical room door might have a ventilation factor of about 2.5 $m^{5/2}$. This would indicate a flashover condition of about 2500 kW as computed from Equation 9.10. With enough fuel in the room, the fire would jump to a ventilation-limited state of just under 4000 kW. The temperature rise at that point could be computed to be about 670°C. This graph shows the firepower in the room, but the fuel generation rate after the fire becomes ventilation limited can produce excess fuel that burns outside the room.

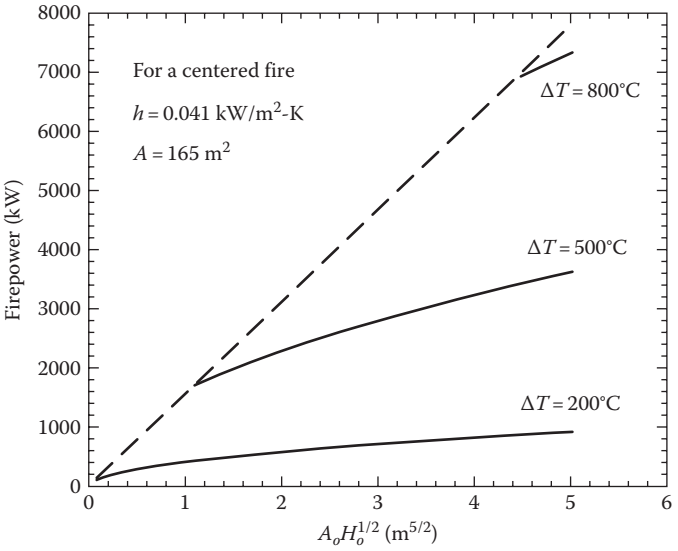


FIGURE 9.23
Firepower for fuel-controlled and ventilation-limited conditions, an example.

9.5.7 Fully Developed Fire Size

Equation 9.11 gives the energy release rate within the room if the fire is ventilation limited. The maximum fuel burning rate depends on what fuel is in the room. For typical rooms in a house, fully developed fires are 800°C or higher. That temperature corresponds to a radiant heat flux (σT^4, T = 1073 K) of about 75 kW/m^2. From Chapter 6, we saw that the heat of gasification may range from about 1 to 10 kJ/g for different fuels. The imposed heat flux and heat of gasification can allow us to compute the fuel production rate from the solid or liquid fuels.

Example 9.4

Consider a continuation of Example 9.1 (4 × 4 × 3 m high, and 1 × 2 m high wall vent). But now the fuel is allowed to burn according to the fire conditions. Assume an average heat of gasification (L) of 3 kJ/g for the room contents. Consider a heat flux of 75 kW/m^2 caused by the smoke in the fire's fully developed state. Consider this fuel distributed over the floor area A = 16 m^2. Then from Equation 6.1 the generated gaseous fuel rate is computed as

$$\dot{m} = \frac{75 \text{ kW/m}^2}{3 \text{ kJ/g}} \times 16 \text{ m}^2 = 400 \text{ g/s}.$$

If the average heat of combustion, ΔH_c, is taken as 20 kJ/g, then the corresponding fire size (Equation 6.3) is

$$\dot{Q} = (400 \text{ g/s})\,(20 \text{ kJ/g}) = 8000 \text{ kW or } 8.0 \text{ MW}.$$

From the ventilation factor of 2.83 $m^{5/2}$, Equation 9.11 gave a ventilation-limited fire of about 4400 kW within the room. The remaining energy release rate, 8.0 – 4.4 = 3.6 MW, must potentially burn outside of the room.

This dramatic increase in the firepower shows the consequences of flashover leading to a ventilation-limited fully developed fire. If instead of just considering fuel distributed over the floor we had said the enclosure was completely lined with fuel, for example, combustible interior finish, then the entire enclosure surface area (minus the vent opening, 2 m^2) gives A = 78 m^2. Subsequently, we compute the corresponding fuel generation rate $\dot{m}$ = 1950 g/s and the fire size $\dot{Q}$ = 39 MW.

The hazard of combustible interior finish, even thin ones, is clearly demonstrated. Figure 9.24 shows the possible fire growth behavior of this room fire example. The fully developed fire state depends on the nature and extent of the fuel available to burn. Flashover begins at about 2.6 MW, it ends with a ventilation-limited fire at 4.4 MW, and the fire can produce fuel that continues to burn outside the room with a total output of 8–39 MW. The latter is for lining materials that fully expose their surface area to the heat of the fire in the room.

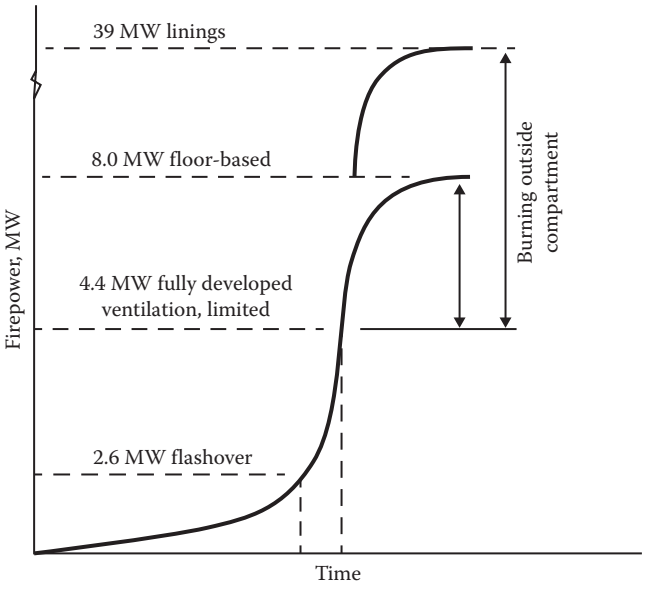


FIGURE 9.24
Fire growth of example fire scenario.

These differences in total fire output show the effect of heat transfer; however, the decrease in oxygen feeding the fire will mitigate these estimates and reduce them. Here, we have selected a heat flux of 75 kW/m^2 indicative of the smoke layer heating. The flame also causes additional heating, and it is affected by oxygen. Vitiation reduces the flame temperatures and as a result the burning rate. The decrease in oxygen feeding the fire is due to the vent mixing into the lower layer as shown in Figure 9.11. Let us see how to include this effect.

9.5.7.1 Model for Fuel Generation in a Compartment

It is very important to understand the production of fuel gas generated in a fully developed compartment fire. The rate of its generation controls the firepower to the surroundings, and it controls the duration of the fire. The latter is critical to the fire's effect on the structure. A model that illustrates the competing effects of oxygen and heat transfer on the fuel generation was introduced in the work of Utiskul.[9] It simply says that the mass loss rate by direct flame heating depends on the oxygen concentration supplied to the flame, and the fuel-exposed surfaces generate mass due to radiant heat transfer from the compartment smoke and ceiling. Some of this heat transfer cannot fully strike the surface, as it can be absorbed by a thick flame or the fuel surfaces are not exposed or hidden from radiation. Representative fuel categories can be a pool fire on the floor whose surface is always exposed and a crib fire that has hidden surfaces. The pool fire can represent lining materials or flat surfaces, and the crib can represent structural furniture. An equation for the model is quantitatively given as

$$\dot{m}_F = \dot{m}''_{F,o} A_{F,b} \frac{Y_{ox,l}}{Y_{ox,o}} + \frac{\dot{q}_{External}}{L} \tag{9.12}$$

where

$Y_{ox,l}$ is the oxygen mass concentration in the lower layer supplied to the flame
$Y_{ox,o}$ is the oxygen mass concentration normal air at 0.233
$A_{F,b}$ is the surface are covered by flame
$\dot{m}''_{F,o}$ is the burning flux in normal air
$\dot{q}_{External}$ is the radiant heat transfer rate from the compartment

The burning flux in normal air can be determined by measurement or estimated from the maximum burning fluxes in large fires. The amount of radiant heat flux that can get through the flame depends on the size of the flame. In small-scale laboratory experiments, the flame is small, and the smoke radiant heating effect is large. But for large realistic fires, the smoke radiant heat has difficulty in penetrating the flame. So the heat feedback effect from the smoke is less for big fires.

To exercise this formula many things have to be known: The radiant heat, how much gets through the flame, the oxygen feeding the fire, and the type of fuel. A complete model of the compartment fire must be used to integrate all of these effects. This was done in the work of Utiskul,[9] and we will shortly show some of those results to illustrate quantitative effects.

A significant aspect of ventilation-limited fires is that flames do not cover all of the fuel heating. The area of fuel covered by the flame ($A_{F,b}$) is less than the total exposed area of the fuel. It can be estimated by knowing the stoichiometric air-to-fuel ratio ($s = \Delta H/(3\ \text{kJ/g-air})$) and the supply rate of air to the compartment:

$$A_{F,b} = \frac{\dot{m}_{air}}{s} \Bigg/ \left(\dot{m}''_{F,o} \frac{Y_{ox,l}}{Y_{ox,o}} + \frac{\dot{q}''_{Ext,b}}{L} \right) \tag{9.13}$$

with $\dot{q}''_{Ext,b}$ the compartment radiation heat flux to the flaming surface.

Essentially this equation is derived by equating flaming firepower over the area, $A_{F,b}$, (from Equation 9.12) with the maximum possible firepower due to air supply (Equation 9.11).

9.5.7.2 Fully Developed Compartment Fire Behavior

A collection of data assembled by Utiskul[9] taken from Harmathy (Ref. 17 of Utiskul[9]) for crib fires and from Bullen and Thomas (Ref. 20 of Utiskul[9]) for liquid pool fires in compartment experiments is shown in Figure 9.25 along with his data for the same. His data were developed in a rectangular compartment 0.4 m high (Figure 9.26) with an array of wood cribs or pans of heptane distributed over the floor. The data in Figure 9.25 scatter due to the scale of the compartment and the heat transfer losses. But they show a trend that is very clear. The fuel gasification rate per unit area has a power relationship (about 0.6) with the ventilation factor divided by the total fuel exposed area, A_F. Also notice that the pool fire data (x's) have higher mass flux levels than the crib (+'s) data. This is to be expected because of the greater effect of radiant feedback for the pool fires. The horizontal axis represents a parameter related to the equivalence ratio. Recall the equivalence ratio is defined as $\Phi \equiv (\dot{m}_{fuel} s/\dot{m}_{air}) \propto (A_F/A_o\sqrt{H_o})$ and is therefore related to the reciprocal of the axis parameter. So as the horizontal axis parameter decreases (Φ increases) and the fire state becomes more ventilation limited. At high values along the axis, the fire is fuel controlled. In this region, there is a tendency for the crib and pool mass fluxes to level off. These tendencies are more clearly indicated in just the data of Utiskul and his computations shown in Figure 9.27.

Figure 9.27 shows computations for a specific ratio of compartment surface area (A) to fuel exposed fuel surface (A_F), along with representative data for pool and crib fires. The effect of scale has been computed as well for a compartment four times bigger (1.6 m high) than the experiments (0.4 m). The accuracy of the computations can only be judged by comparison to the small-scale data in

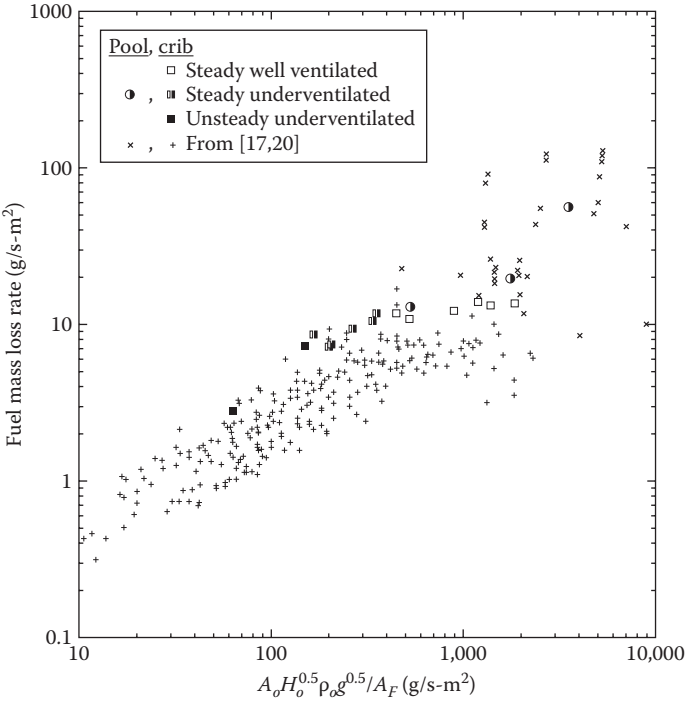


FIGURE 9.25
Fuel mass flux as a function of ventilation to fuel area ratio for pool and crib fires. (From Utiskul, Y., Theoretical and experimental study on fully-developed compartment fires, PhD thesis, Department of Fire Protection Engineering, University of Maryland, College Park, MD, 2008.)

FIGURE 9.26
Compartment fire experiments. (From Utiskul, Y., Theoretical and experimental study on fully-developed compartment fires, PhD thesis, Department of Fire Protection Engineering, University of Maryland, College Park, MD, 2008.)

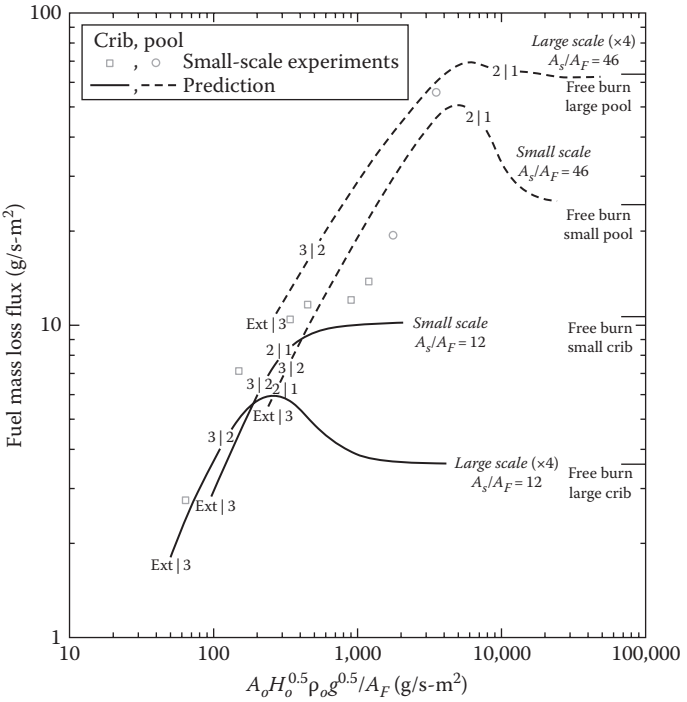


FIGURE 9.27
Effect of fuel type and scale in fully developed fires. (From Utiskul, Y., Theoretical and experimental study on fully-developed compartment fires, PhD thesis, Department of Fire Protection Engineering, University of Maryland, College Park, MD, 2008.)

Figure 9.27 as well as those in Equation 9.25. The theoretical result has not been fully validated but its trends have credibility. So it can serve as a good illustration of variable behavior and scale effects. As $\rho_o \sqrt{g} A_o \sqrt{H_o} / A_F$ increases the fully developed fire state moves from a ventilation-limited to a fuel-controlled state. As the fuel exposed area becomes very small relative to the enclosure size, the fire approaches a free burning fire in the open. Here, there is a reverse in the scale effect between cribs and pools. As the scale increases for a crib, its thicker sticks burn at a slower rate per unit area compared to small scale ($\dot{m}'' \propto thickness^{-1/2}$. In contrast, the larger-scale pool fire can achieve a higher free burn mass flux than its smaller-scale turbulent counterpart.

As $\rho_o \sqrt{g} A_o \sqrt{H_o} / A_F$ decreases from its highest value, the fire conditions moves through several stages in the following order:

1. Steady well-ventilated, fuel-controlled fire
2. Steady underventilated fire
3. Unsteady oscillating, underventilated fire

Ext. Extinction of flames.

The theoretical curves are labeled with these regime boundaries. The boundaries depend on scale and are different for the wood cribs and heptane pool fires, as each requires different stoichiometric values: heptane, 13.7 g air/g fuel; and for wood about 4 g air/g fuel. Extinction is based on the flame temperature falling below its critical value needed for burning. The oscillating region occurs for relatively small vents. Oscillation occurs due to vitiated oxygen that drives the flame to extinction, followed by a subsequent cooling effect that lowers the compartment pressure causing a new inflow of fresh air. The new air revitalizes the fire, and the process repeats—sometimes continuing until all of the fuel is depleted. A photograph showing this sequence is displayed for a crib fire in Figure 9.28. A more dramatic effect is depicted in Figure 9.29 for pools distributed over the floor of the compartment in underventilated burning. The flames begin by covering all of the fuel as there is initially enough oxygen. As the oxygen is reduced, the flaming is reduced and flames move toward the vent. The flames seek the air. As the flaming fuel is depleted, the flames would then move back to the remaining fuel. This condition is commonly responsible for deep damage, in extinguished

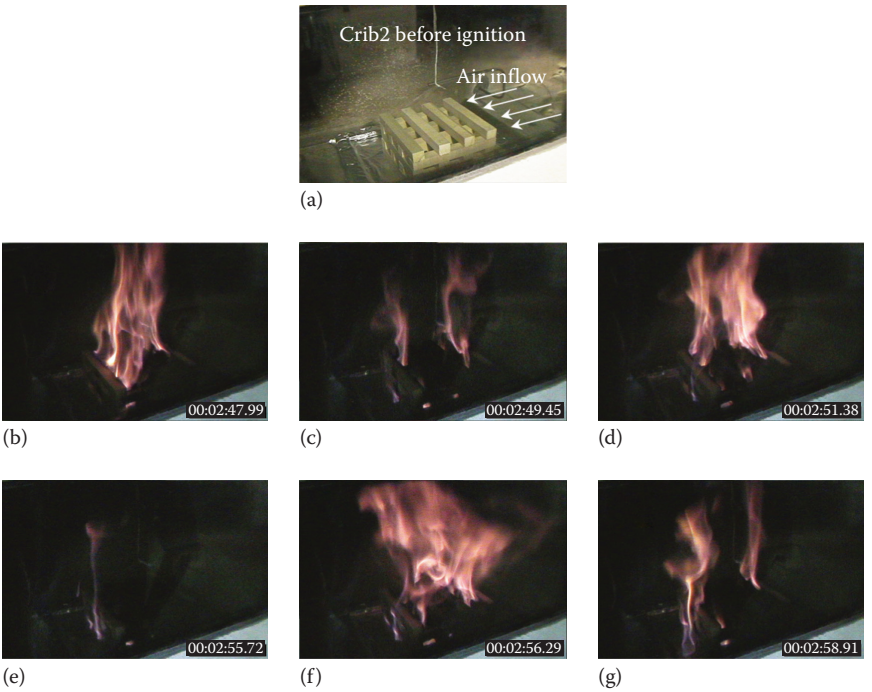


FIGURE 9.28
Oscillatory burning for a crib fire in a compartment: (a) configuration; (b, d, f) growing; (c, e, g) dying. (From Utiskul, Y., Theoretical and experimental study on fully-developed compartment fires, PhD thesis, Department of Fire Protection Engineering, University of Maryland, College Park, MD, 2008.)

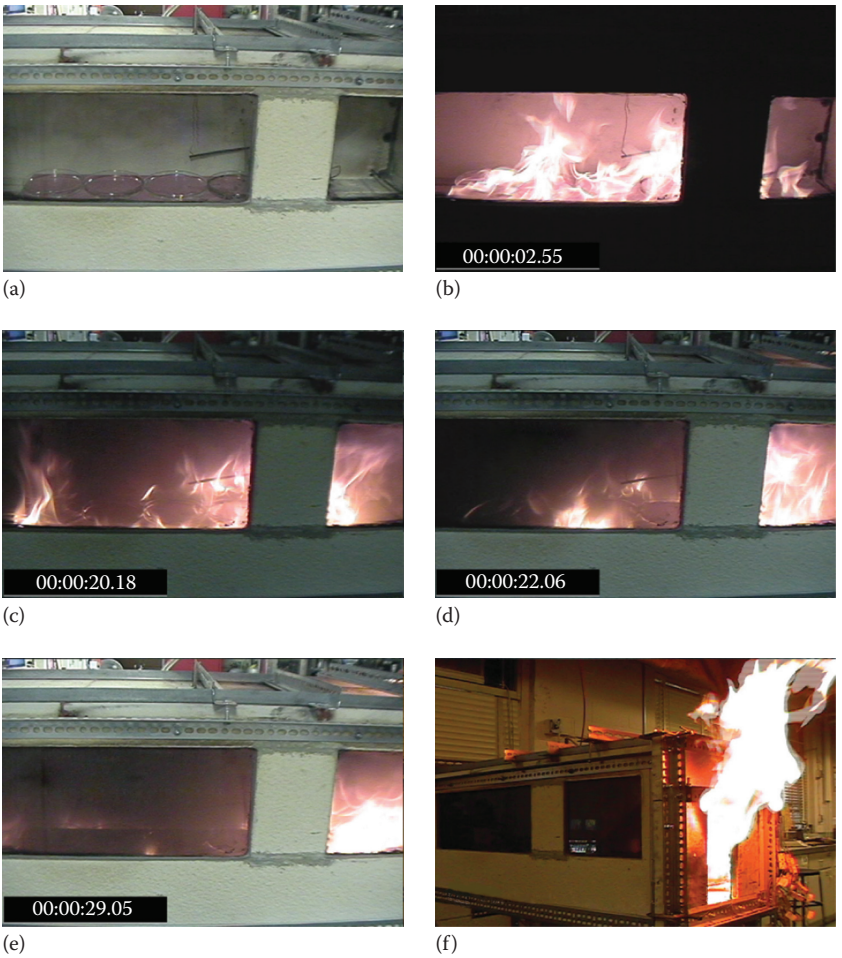


FIGURE 9.29
Early fire growth in underventilated burning of heptane pools showing reduced flaming as initial oxygen is reduced and flames move to the vent. (a) Heptane pan layout. (b) Full area burning. (c) Burning at ~60% A_F. (d) Burning at ~40% A_F. (e) Burning at ~20% A_F. (f) Ventilation limited burning. (From Utiskul, Y., Theoretical and experimental study on fully-developed compartment fires, PhD thesis, Department of Fire Protection Engineering, University of Maryland, College Park, MD, 2008.)

house fires, occurring near the vents as well as at the origin of the fire. Past investigative principles suggested this to be two fires and arson as the cause!

9.5.7.3 Fuel Load and Burning Duration

An important aspect of a compartment fire is not only its temperature but its duration. The burning duration can be calculated by dividing the mass of fuel available by the mass supply rate of gaseous fuel. For a structure to

TABLE 9.2

Fuel Load in Mass Per Unit of Floor Area

Occupancy	Fuel Load (Per Floor Area) Mean Value (kg/m²)	Standard Deviation (kg/m²)
School classroom	40.5	16.9
Apartment house bed room	44.6	10.7
Apartment house living room	34.7	23.2
Apartment house storage room	55.5	32.6
Office room	39.2	34.7
Office library	146	68
Office meeting room	6.4	1.4
Hotel guest room	10.6	1.6
Hotel banquet room	3.3	1.2
Athletic area	2.5	2.3

Source: Natori, A., *Fire Sci. Technol.*, 27(3), 310, 2008.

be safe, the burning time should be less than the rating time for a structural element in simplest terms. In other words, the fire should burn out before the structure is damaged. The available fuel burnable mass has been associated with the occupancy of a building, and fuel load surveys have been carried out to characterize occupancies. Each particular occupancy has variations, and we will express these in terms of a mean value and a standard deviation. Natori[10] presents such information based on fuel load surveys conducted between 1973 and 1996. These come from Japanese literature but are indicative of global characteristics. The results are given in Table 9.2. It is seen that in some cases, the standard deviation is significant compared to the mean, showing a wide possible range for an occupancy.

These data are crucial in the design of safe structures for fire. Formulas from fire dynamics can give the temperatures and the burning rate. The occupancy fuel load then will allow computation of the duration of the fully developed fire. We have seen that the fully developed fire is usually ventilation limited and the fuel mass loss rate is determined by the ventilation factor. So fuel quantity and ventilation openings are key in determining the duration of a compartment fire.

9.6 Anatomy of Fire Growth

Observations of fire are crucial to learning. Today inexpensive video cameras that might be sacrificed in the fire are valuable aids. In 2009, the ATF Fire Laboratory and the International Association of Arson Investigators conducted fire tests to examine damage after flashover. This was produced into a training module for CFI-Trainer available at

https://www.cfitrainer.net/Training_Programs/Postflashover_Fires.aspx.

An examination of these data and video records vividly show the behavior of fire as it moves through its stages. It clearly shows the onset of flashover and the start of the ventilation-limited fire. It shows the movement of flames from the origin to eventually the doorway. A review of the data and stills of the videos will try to illustrate these effects.

A schematic of the bedroom where the fire occurs is shown in Figure 9.30. The significant instrumentation for this discussion is described as follows:

- Thermocouple tree TC-B: running from the floor (B-0) to the ceiling (B-8), in 1 ft increments
- Heat flux meters: THF-A (total), RHR-A (radiation only), THF-B (total), THF-C (total), all at 1.22 m from floor
- Oxygen: GS-A (at 0.19 m above floor), GS-B (as 2.22 m above floor), GS-C (at 0.15 m above floor), GS-D (at 1.16 m above floor)

The fire is started in a plastic waste basket, filled with paper, that is between the bed and the chair. The clock recording data is begun before ignition occurs at 0:19 (minutes:seconds). By 1:00 the sides of the bed and chair are ignited (Figure 9.31a).

At about 2:30, the temperatures at the room center near the ceiling begin to rise sharply (see Figure 9.32). This was preceded by the onset of accelerating flame

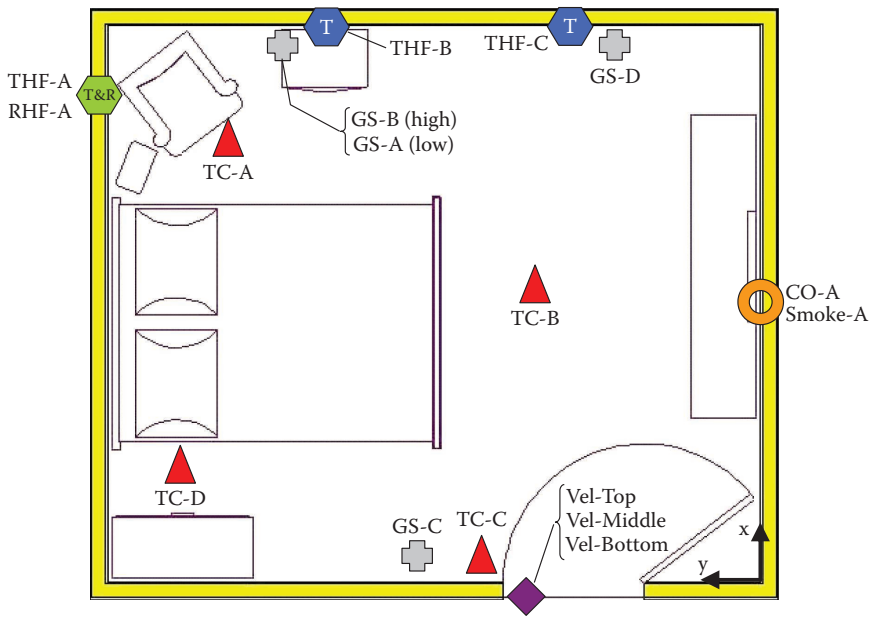


FIGURE 9.30
Bedroom schematic showing furnishings and instrumentation. (From ATF Fire Laboratory.)

spread over the top of the bed and the back of the chair (Figure 9.31b through d). At 2:15, a blackened top-left corner of the chair-back indicates the start of the spread. This flame spread began at about 2:15, accelerated, and ended covering most of the chair at about 3:02. In Figure 9.32, the beginning and end of the rapid rise in gas temperatures nearly coincide with the onset of this rapid spread and its end, occurring between about 2:15 to 2:30 and 3:00, respectively. This marks the beginning and end of flashover, a 30-second duration.

Notice that before the onset flashover, the heat flux meter on the wall adjacent to the fire origin (THF-A) achieves a heat flux of 200 kW/m^2 (Figure 9.33). It sees a thick impinging flame igniting basket flame merging with flames on the side of the chair, as shown in Figure 9.31b. This heat flux is due to convection and radiation from the flame. In contrast at the same time, the heat flux away from the origin, halfway up on the rear wall (THF-B) has a much lower value. This sensor "sees" the upper smoke layer with about a 50% view angle. This is nearly the same view angle to the upper smoke layer as a heat flux meter on the floor away from the origin would see. Hence, THF-B on the wall is approximately indicative of a floor heat flux away from the origin. At the onset of flashover (2:15–2:30), it primarily reads radiation at about 20 kW/m^2. At the end of flashover, it attains over 100 kW/m^2 (~3:00). These are

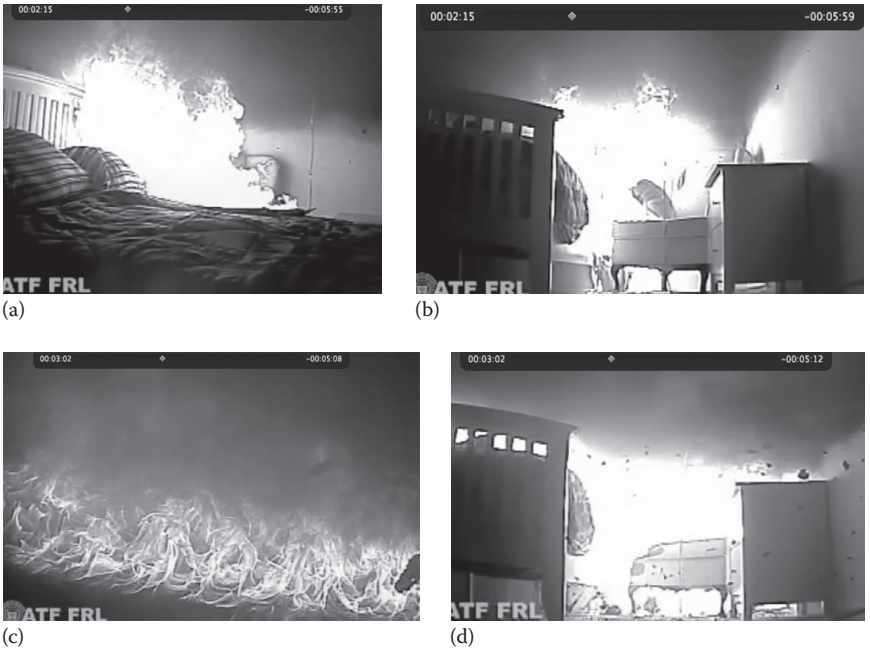


FIGURE 9.31
Sequence of events in bedroom fire development. (a) ~ 1:00 Ignition of the sides of the chair and bed. (b) 2:15 Onset of rapid flame spread on the chair back. (c) 3:00 Flame has spread completely over top of bed. (d) 3:02 Flame has spread completely over chair back. (*Continued*)

(e)

(f)

(g)

(h)

FIGURE 9.31 (*Continued*)
Sequence of events in bedroom fire development. (e) 2:58 Black layer of smoke drops to near the floor in the room. (f) 3:44 Flames move away from the origin region. (g) 4:09 Flames begin to move toward the door. (h) 4:30 Flames emerge from the door.

typical values just before and just after flashover. That is why 20 kW/m^2 is a common benchmark for computing flashover.

It is also instructive to examine the oxygen concentration in the smoke layer (GS-B, Figure 9.34) at the beginning and end of flashover. At about 2:30, it is about 0.12 (12%), then begins to drop precipitously to zero (ventilation limited) at 3:00. At this time, the oxygen levels (Figure 9.34) near the floor (GS-A and C) are still near pure air levels of 21%.

Also during flashover, the smoke layer interface in the room drops from about 1 m to about 40 cm and then continues to drop as the compartment gets hotter. By 2:58 (Figure 9.31e), it is now at 20 cm and remains there. Notice that the neutral plane in the doorway is higher at about 1 m.

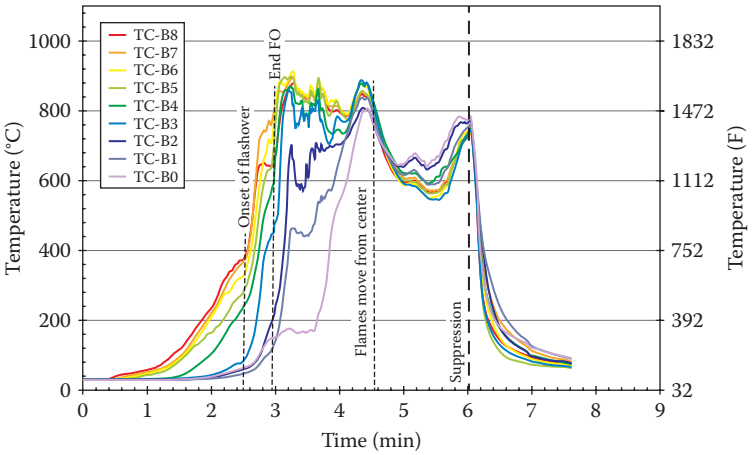


FIGURE 9.32
Temperature vertical array at the center of the room. (From ATF Fire Laboratory.)

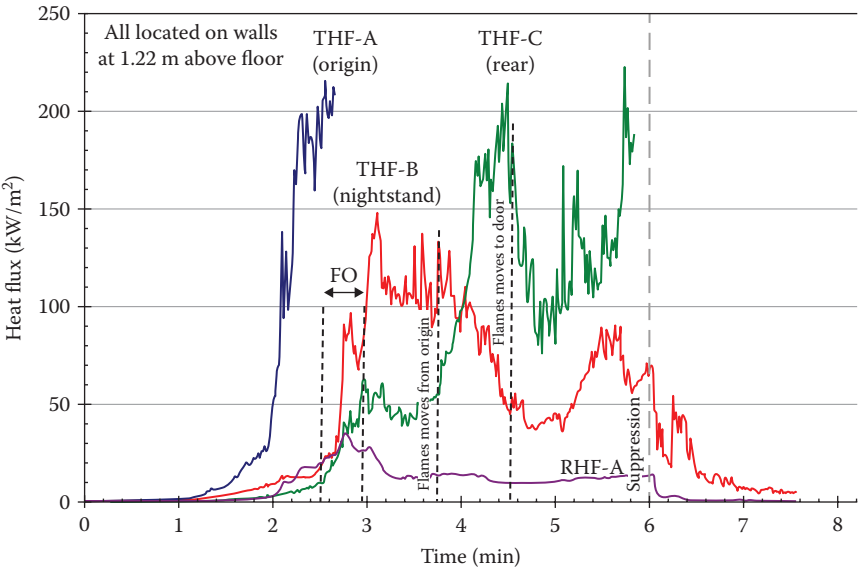


FIGURE 9.33
Heat flux sensors: THF-A (total), RHR-A (radiation only), THF-B (total), THF-C (total) all at 1.22 m from floor. (From ATF Fire Laboratory.)

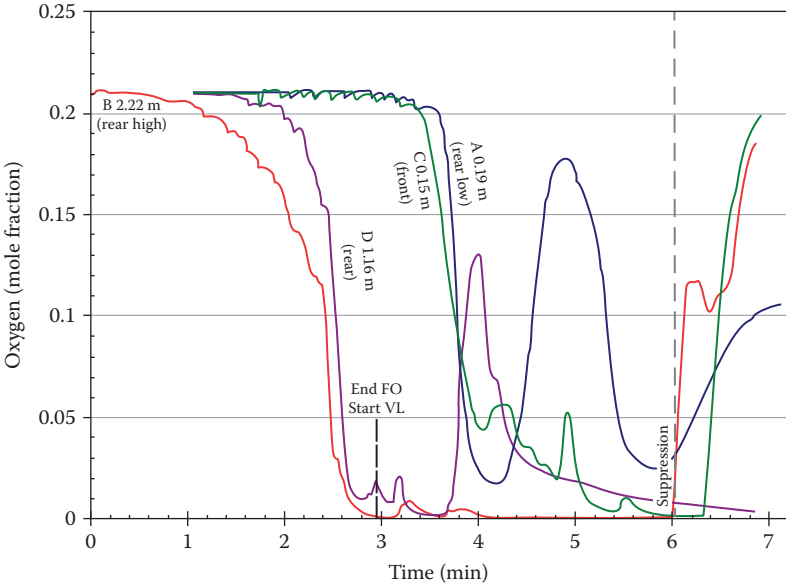


FIGURE 9.34
Oxygen concentrations: GS-A (at 0.19 m above floor), GS-B (as 2.22 m above floor), GS-C (at 0.15 m above floor), GS-D (at 1.16 m above floor). (From ATF Fire Laboratory.)

Clearly these illustrations and data show that flashover is a process of rapid fire growth brought on by increases in heat flux from the smoke layer over the bed and chair back in this case. This sends the smoke layer down toward the floor, temperatures in the smoke layer sharply rise, and its oxygen drops. For this fire, the end of flashover is marked by a ventilation-limited state of zero oxygen in the smoke. If less fuel were in the room, it could have ended in a fuel-controlled fire with all of the combustible material covered by flames.

During the ventilation-limited fire, the flames do not cover all of the fuel. Indeed, Figure 9.31f at about 3:44 the flames move away from the origin toward the right rear wall (as facing from the doorway). A confirmation of this flame movement is indicated by the drop in the heat flux near the origin (THF-B) as the flames move away, and an increase in the wall heat flux closer to the right rear (THF-C) as flames are felt (Figure 9.33). Also the oxygen level at the origin near the floor (GS-A) starts to drop at about 3:44 and by 4:00 is about 2%. This indicates that the inflow of air is hardly reaching this left corner. The flow of air is now directed to the right side of the back wall where there is flame. (See the increase of oxygen at GS-D in Figure 9.34.) There is not much to burn in this region, mostly carpeting. Consequently, by 4:35 the flames move again from the right rear area to the door, and flames emerge from the door (Figures9.31g and h). At this time (4:35), the flames engage the thermocouple array TC-B, and as the carpeting is now burning there, their temperatures over the entire vertical array become nearly uniform.

Some have called the event of the emerging door flame, flashover, as there is an obvious presentation of flames to suggest all the room is now burning. This is false according to the concept that flashover is an instability that leads the fire to a ventilation-limited or fully developed fuel-controlled state. Only a portion of the room has flames; now, primarily near and in the doorway. This is corroborated by no flames shown from the view looking at the right rear floor (Figure 9.31g), only smoke. Also, the center temperatures (TC-B) become uniform and all start to drop shortly after 4:35 and continue until after 5:00.

Unusual oxygen sensor behavior indicates maxima after the flames move away from the origin. As flames move to the right rear, the incoming flow is entrained there and the oxygen (GS-D) at the back wall increases to about 13%, then drop again as the flames move forward to the doorway. This effect of turbulent flames impinging on the right rear gypsum wall could result in a *clean burn*. Such a pattern is caused by the soot being burned off the wall and remaining in that state. The subsequent oxygen drop in GS-D indicates that the flames leave this area.

The most unusual behavior is the rise in oxygen for GS-A at the origin near the floor. After 4:00, it increases to about 18% at 5:00, while in this same location, the oxygen is still 0% in the smoke layer (GS-B). This unusual effect might be explained by a sharp increase in airflow rate from much higher temperatures near the doorway due to the burning carpet. The increase in airflow could cause a high-velocity floor jet of fresh air with enough momentum to reach the rear, especially by the path under the bed. If oxygen reaches this origin area and there is still remaining fuel, flames can reappear there. It appears that they did reappear as exhibited by the heat flux sensors (THF-B and C) increasing after about 5 minutes. As seen, complex behavior can occur after flashover and a ventilation-limited state is achieved.

The ventilation-limited state clearly needs more study. It increases the production of incomplete and toxic combustion products. The duration of the fire, significant to the safety of structures in fire, depends on the air supply. The flames within the compartment move to essentially seek oxygen. The deposition of soot on plaster walls depends on the presence of oxygen-rich turbulent flames. Eventually the flames emerge from vents with a flourish. This dramatic event is not "flashover." Hopefully, the portrayal of this bedroom fire has enlightened an understanding of the processes in room fire development through flashover to its fully developed state.

9.7 Summary

Fire grows in a room in stages: first, a nearly free-burning stage without any influence from the room; then flashover can occur; followed by the fully developed state, which is likely to be ventilation limited for typical furnished

rooms. After extinction of flames, smoldering can persist and this is a cooling stage. Flashover is an instability between heat released by combustion and energy losses. It manifests its occurrence by rapid fire growth due to increasing heat flux from the upper smoke layer. A sudden increase in room temperatures marks the onset of flashover. A leveling off of these temperatures marks the end of flashover and the start of the fully developed fire. Oxygen depletion in the lower layer causes the fire to diminish and, in cases of poor ventilation, possibly extinguish. A level of zero oxygen concentration in the exiting smoke defines the ventilation-controlled fire. Combustion in this state is controlled by the airflow rate. In this state of insufficient air, the flames in the room will fill only a portion of the room and will move to the vents where air is entering. As flames exit the room, some might call this "flashover" but it is not. If oxygen does not drop to zero in the smoke, the fully developed fire is fuel controlled and all the fuel in the room can support flames.

Small pressures drive the flows associated with fires in rooms. In multistory buildings, normal air-conditioning for heating and cooling, as well as fire effects, leads to a stack effect that controls buoyancy for the entire building. Without a dominant stack effect, the fire-induced flows can exceed pressures due to air conditioning ducts and disrupt those duct flows. The flow processes in a room fire begin with plume rise to the ceiling, a formation of a ceiling jet about 1/10th of the room height, then a stratified layer forms and descends. In a closed compartment, it can nearly reach the floor. Otherwise, an open wall vent will lead to a bidirectional flow with air in and smoke out. The flow system can approximately be considered as an upper smoke layer and a cooler lower layer with fairly uniform temperatures and gas concentrations in each.

Formulae exist for estimating smoke filling, smoke layer temperature, and vent flow rates. These show how to estimate the firepower needed for flashover and ventilation-limited conditions.

Review Questions

1. For your classroom estimate the energy release rate needed to initiate flashover. Assume the door is open. What kind of fuel package might this represent?
2. What fire size (kW) will cause a 300°C smoke layer temperature in your room with the door half open? What is the maximum radiant heat flux associated with smoke of 300°C?
3. If your room reaches flashover and becomes fully developed reaching 800°C, what is the maximum air flow rate through your fully opened door? If all the windows break, what is the additional air flow rate? What fire size can be supported by these total air flow rates? Is there sufficient fuel in the room to do it?

4. A tall building on a winter day has an indoor temperature of 23°C and an outdoor temperature of 0°C. Its height is estimated as 350 m. What pressure difference would result over a shaft of this height? If the shaft has an effective diameter of 3 m, what is the average velocity of air moving in the shaft? Assume it is fully open at the base and top of the building. (See Equations 9.3 and 9.4.) Let $f = 0.02$.
5. Assume a smoldering chair fire occurs in your classroom, and the doors and windows are shut. Using the information in Figure 9.19, estimate the time the smoldering fire smoke layer reaches the fire location at 1.2 m above the room floor (t_o). Also, estimate the time to achieve an incapacitation from CO at that location (t^*).

True or False

1. Fires in a room with a door or window open, producing smoke of less than 200°C, can be considered a developing, almost free-burning fire.
2. Smoldering fires typically in a room produce lethal conditions in less than 10 minutes.
3. Backdraft is a form of flashover.
4. In the summer, fire in a high-rise air-conditioned building can have smoke propagate to the floors below the fire.
5. A fire in a vessel eventually has to go out due to oxygen depletion or it may burst the vessel.
6. Pressures associated with air handling ducts can dominate the flows of a big building fire.
7. Flashover occurs when flames discharge from a room.
8. Flames do not fill a room in a ventilation-limited fire.
9. Smoke forms a ceiling jet and the inlet air flow can form a floor jet.
10. Oxygen can never get to zero concentration in a room fire.

Activities

In a laboratory with safe operating and extinguishing systems, conduct some room fire experiments. Build a small compartment between 1 and 2 ft in height. Allow for various window and door openings. Use small pool or crib fires. Measure the temperature at the exit. Conduct various experiments to reveal the stages of fire. Take care in ignition, and never leave liquid fuel sitting in the compartment for a long time before ignition.

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Design, Investigation, and Case Studies

Learning Objectives

Upon completion of this chapter, you should be able to

- Appreciate analytical applications in fire safety design and in fire investigation
- Understand performance-based design
- Understand the role of science in investigation
- Explain fire modeling in terms of equations and computer solutions

10.1 Introduction

Having completed the previous chapters, it should be clear that methods exist for estimating the size of a fire and its growth, $\dot{Q}(t)$, and for estimating its damage effects from heat and smoke. Also, it should be clear that this process is complex, and we have only considered simplified methods for estimating aspects of fire growth. Nevertheless, it is possible to step through a fire scenario using our equations with good results and reasonable accuracy. Most fire phenomena have uncertainties due to circumstances not completely known (e.g., the extent of a door opening, the proximity of one item to another). Even if we know all of these factors, our computations are not perfect, varying in accuracy by as much as ±50%, but usually much better. Yet these approximate analyses can still be very useful, even with these limitations. They serve to provide guidance in design and direction in fire investigation. Both of these applications do not require high precision. If time is the important factor being considered in a fire phenomenon, it might be estimated in seconds, minutes, or hours. That level of accuracy should be enough to make conclusions. This level of accuracy is not exclusive

to fire but to all forms of investigation and design. The analysis must give a means to make informed decisions.

The use of science in fire is increasing. In fire safety design, the performance-based design is gaining widespread acceptance around the world. This approach is an alternative to a plank-by-plank following of detailed regulations. The performance-based approach considers the safety issues associated with the specific fire challenge and renders a design to achieve a quantitative engineering performance. In fire investigation, U.S. Supreme Court decisions (Daubert and Kumo Tire) have mandated that expert testimony has a scientific basis. This does not mean that science alone must serve as the investigator, but that opinions must have followed a scientific method. The facts must be gathered and analyzed, and hypotheses accordingly evaluated for consistency. The analyses must include relevant testing or computations to support an opinion in court. Usually, the question asked of an expert is "… to a reasonable degree of scientific certainty what is your opinion?"

In this chapter, we will consider the science-based aspects of fire safety design and fire investigation. In fire safety design, a specific fire is not obvious and many scenarios and their probability must be considered. In fire investigation, we may have some evidence or hypothesis of the fire. An important aspect of design and investigation is the justification of the relevant fire scenarios and the probabilities of their occurrence. In investigation, we might use our calculations to clearly eliminate or accept a certain event and its time of occurrence. In design, we might rule out a hazard from worst-case fire considerations. We will discuss these two applications more.

To illustrate the applications to design and investigations, some case studies will be introduced. In addition, a discussion of the use of computer models will be presented. Such models are part of our new technology and many people become versed in their use. Some are easy to use, and others require computer skills. Hopefully this book has provided background to appreciate the ingredients of computer models. A bit more will be said about this later, but the user of any model—equation or computer—must understand its relevance and limitations. Misapplied, both can be misleading and misunderstood.

10.2 Fire Safety Design

Design in fire safety is used principally in establishing compliance with the local regulations. These regulations, based on codes and standards of practice, specify the requirements. The architect, builder, or building owner must ensure compliance. To do more is not usually sought; however, many situations arise where the regulation is not clearly applicable or the

designer wishes an equivalent alternative. The establishment of *equivalency* requires at least a technical discussion but more appropriately an analysis. To truly meet an equivalency to the regulation, it must be interpreted into a performance-based statement, and the parties have to agree to its correctness. The formulas we have discussed for fire computations can be used for such equivalency analyses. The *SFPE Handbook of Fire Protection Engineering* referenced throughout this book offers more depth in design formulas than we have had time to discuss.

Performance-based design has taken hold globally in fire safety design. In my view, its engineering practice began in Japan. Indeed, Japan had an engineering handbook for fire well before the United States. However, some attribute the formal thought beginnings of this approach to a study in Australia funded by the Warren Centre at the University of Sydney in 1987. While that was a sound study, one motivating factor was to give the steel construction industry a leverage point. Here, that market force helped to bring about a change in the process of regulations for fire. In the United Kingdom, the reduction of government regulations in the Thatcher administration brought about change there. And as engineers in fire were beginning to have true engineering tools, the idea of performance codes caught on. Now in the United States, the International Code Council and the National Fire Protection Association (NFPA) endorse the *SFPE Engineering Guide to Performance-Based Fire Protection.* This modeling-based approach to design issues requires competency, integrity, and completeness. While consensus standards have been developed through an empirical process, the misuse of science can have severe consequences, so performance-based design must be administered with care.

Many aspects of fire are subject to regulation and therefore open to design possibilities. Some areas that apply are listed:

1. Detection and alarm
2. Mitigation of growth and suppression
3. Egress
4. Continuity of operations
5. Structural integrity
6. Refuge and rescue

We have not addressed all of these aspects in our discussion of fire behavior. The SFPE handbook can give a good overview on ways to predict aspects of these subjects. Egress and human behavior in fire is a subject just as important as the growth of fire but is not studied as much. Detection depends on the technology of the detector, but in investigation nonintended fire detectors may be significant. For example, faults in electric wires can be used to orient the source of the initial fire. This is known as "arc mapping" in which beads on copper wires from electrical shorts caused by the fire can show

directionality of fire fire's attack. Other detectors might be security alarms, such as motion detectors and CCTV for surveillance. On the subject of structural integrity, the book seemed to be closed until the devastating WTC failure and collapse of the twin towers. Engineers are now turning again to such design challenges for structures.

Perhaps the more significant aspect of fire safety design is the interaction of fire growth time with egress time. In general, we seek egress time to be less than the time to cause fire damage to people. For all possible fire scenarios and their likelihood (probability), we need to determine the egress time of the building population. Egress time increases as the fire progresses because smoke slows people. On the other hand, the time to cause damage by the fire is inversely related to fire size. As the fire grows, the time for hazard to people decreases. Sprinklers, suppression by fire fighters, and fire resistance barriers all affect this damage time. A qualitative illustration is shown in Figure 10.1. Adding sprinklers could cause the fire damage time to become infinitely long, meaning complete suppression. Adding compartmentation will increase the time for overall damage, but eventually these barriers will fail and transmit heat and smoke. If the fire continues, eventually the time to escape (egress) exceeds the damage time, and people stop moving and succumb. The graph is qualitative and only serves to show the various parameters. But a designer of building safety, in a performance code approach, must make it quantitative and show there are sufficient factors of safety to present a "safe" design. No design can be completely "safe." Note that even sprinklers can be defeated and the fire damage curve would then turn downward again.

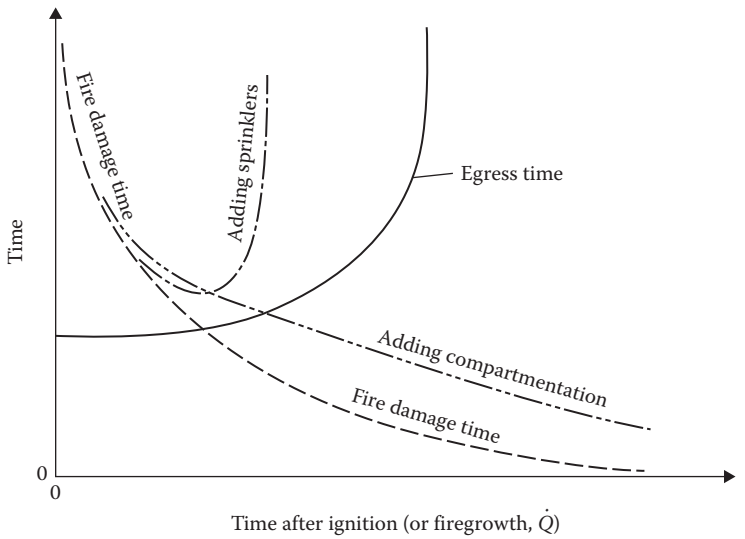

FIGURE 10.1
Fire damage time compared to egress time, for a particular fire scenario.

Sprinkler protection alone is not a sure way to mitigate fire growth. It can fail from poor maintenance and control, and even by design.

10.2.1 Examples in Design

Here are two examples selected to illustrate design-type analyses. Both are based on a computer model used often in Japan for big buildings. The computer code is described in Reference[1] when Dr. Tanaka was a guest scientist at National Institute of Standards and Technology (NIST). This modeling approach is a "zone model" that divides a room into an upper smoke zone and lower zone, and then computes the conservation laws for the gas zones, and boundary elements such as the walls. The Tanaka code formed the basis of the NIST computer code CFAST; however, they are far from the same having evolved separately. The Tanaka code has gone on to become a staple modeling approach by the Japanese construction industry and academia in Japan. An extensive documentation of it in a 2002-upgraded version BRI-2 is available in Reference.[2] That code has widespread use in Japan and has been extended to urban conflagrations as well. The two examples of fire safety design analysis have actually been conducted because of fire incidents; they were not conducted as part of the design process. However, these examples are introduced to demonstrate that such analysis is applicable in the design phase. The analysis of an actual fire incident demonstrates design strategies that could have been applied during development of the building instead of simply applying the regulations. The two buildings discussed in the examples undoubtedly were in compliance with the regulations after construction. Such analyses could have provided cost-effective safety improvements or equivalency to the regulations. Both of these analyses involve the dynamics of smoke in between many rooms in a big building. Our simple equations for flow in this text could not do this type of analysis alone, but this code uses similar physics in a way to account for many flow and fire phenomena at once.

This code is based on a zone modeling approach that solves differential conservation equations for the upper and lower gas layers in a room. With today's computers, this code runs fast, and even a large building can be computed in minutes. Recently, two of our former University of Maryland students used the Building Research Institute (BRI) code as a basis to develop a multiroom fire growth model and its impact on the building structure. This was done for an insurance-based company to assess fire risk (risk management solutions); it combined probabilistic and deterministic modeling.

10.2.1.1 Example 1: Effect of Shaft Vents in a Building Fire

The first example was computed by Takeyoshi Tanaka, a scientist of the BRI of Japan, using his computer code designed to calculate the smoke transport and its properties through a building.[1] The results of the computations are shown in Figure 10.2. Two shaft vent conditions are considered and lead to

slightly different results for smoke movement and temperature. These computations were initiated following the MGM fire of November 21, 1980, in Las Vegas, Nevada. At the time, computers could not easily or quickly compute the 65-story MCM building. So these calculations for only five stories were performed. Their inferences were never used for analyzing that fire or learning from its consequences. Most people (85) died on the upper floors of the MGM as smoke traveled up the vertical shafts. The calculations of Figure 10.2 show that the case of a vent in the center shaft does not affect smoke temperature very much but does impact the smoke depth on the

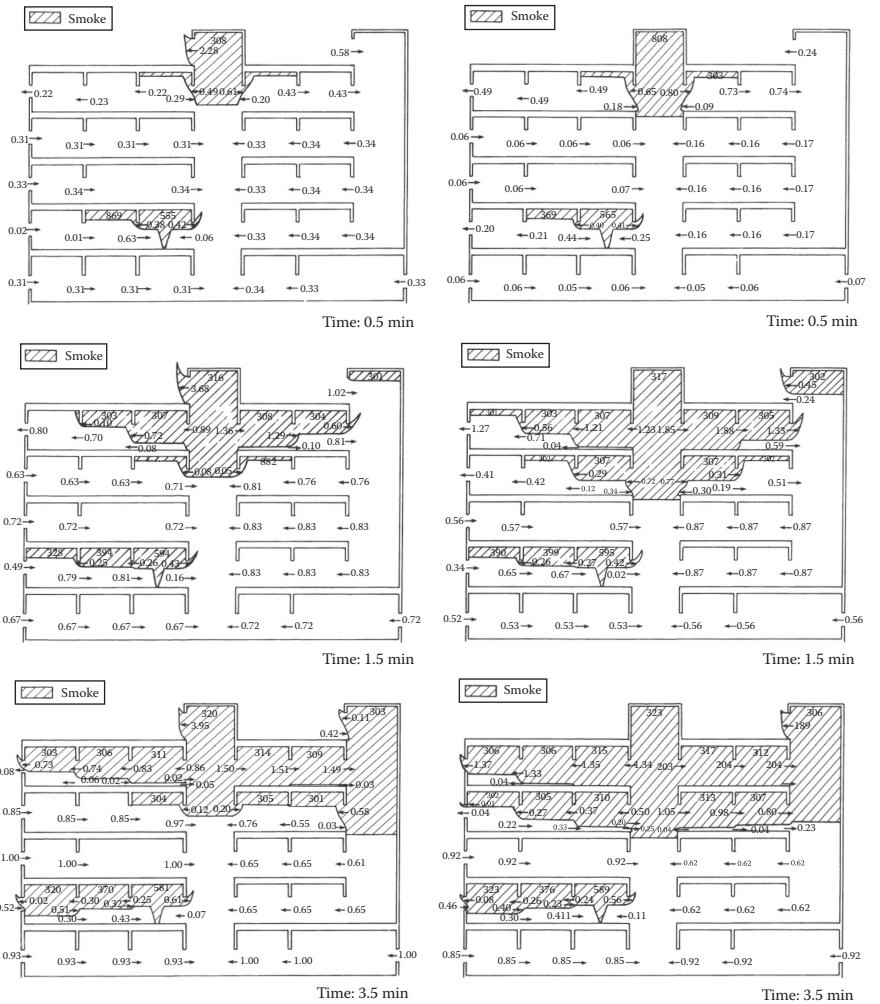

FIGURE 10.2
Smoke movement computations. (From Tanaka, T., A model of multiroom fire spread, NBSIR 83-2718, National Bureau of Standards, Gaithersburg, MD, August 1983.)

third floor. Further calculations could produce more complete information on the benefit of shaft vents. By considering different smoke control options through computations, a designer could determine the best safety for the occupants. The current BRI-2 computer code now can address forced ventilation effects that could be used to address pressurization options in design as well.

10.2.1.2 Example 2: Smoke Movement in the World Trade Center, New York, New York

Another high-rise building fire that attracted much attention was the explosion and fire in the World Trade Center in New York City on February 26, 1993. These computations were implemented by Yamaguchi et al.[3] to analyze the fire scenario of the 1993 World Trade Center fire. An excerpt is shown in Figure 10.3. Computers are now faster and bigger, and this type of zone model can practically compute an entire 110-story building as the WTC towers. A fire of 20 MW for 25 minutes was selected to simulate the parking garage fire (shaded black in Figure 10.3). The results show the smoke flow (black arrows for upper smoke layer flows, white for lower layer flows) at 13 minutes (780 seconds). While this computation analyzed the particular fire scenario caused by the parking garage explosion, other scenarios can be considered in a design strategy coupled with an egress model for the building to assess the impact of smoke and fire on the occupants.

No direct deaths resulted due to the smoke filling the tower building, although it took many hours for occupants to leave the building through the stairways. In this particular fire, the smoke affected visibility but apparently was not toxic. The garage was either well ventilated or the fire never reached the ventilation-limited state to cause toxic smoke to enter the many floors and stairwells. But in a design calculation, a bigger fire and its effect could be considered. I suspect the outcome would be different, and the smoke would be a serious problem for the occupants.

As we can imagine, such calculations cannot only estimate the smoke conditions under this fire event but could be beneficial in assessing the hazard of other fire scenarios. Design strategies that might make the building safer can be evaluated on the computer. So the computer allows the coupling of various fire phenomena and projects them over time. This we cannot easily do by the single equation approach alone. Yet computer models can be checked by the individual formulas to at least see if there is some consistency. This should always be done, or a computer could stray without the awareness of the user.

As we know now, this explosion in a truck bomb in the basement of the WTC was a harbinger of what was to come on September 11, 2001 (9/11). The bomb in 1993 did not dent the massive support column in the basement, but did send smoke through the buildings to such an extent that it took many hours for occupants to egress. We will come back later to a discussion of 9/11.

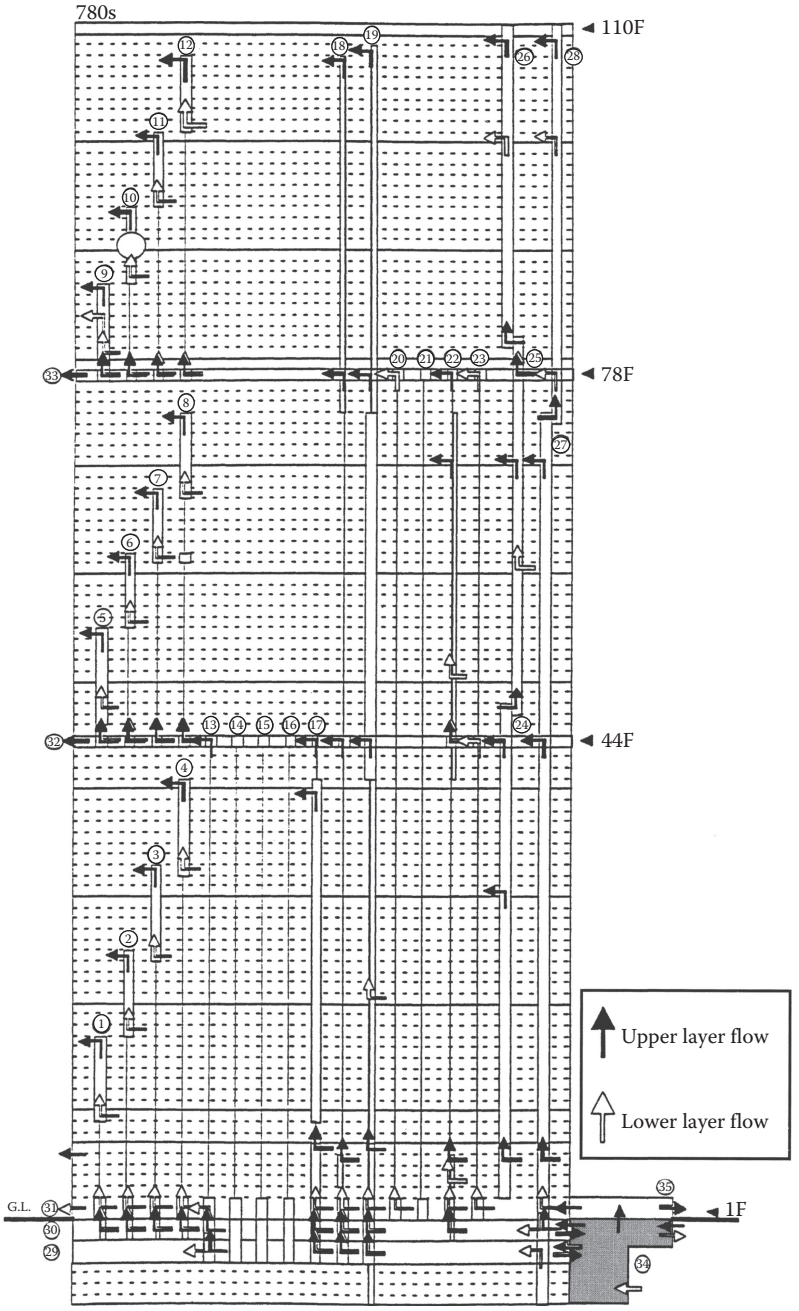

FIGURE 10.3
Analysis of smoke movement in the World Trade Center fire, 1993. (From Yamaguchi, J. et al., A study on predicting smoke transport in a high-rise building [in Japanese], in: *Proceedings of the Annual Meeting,* Japanese Association for Fire Science and Engineering [JAFSE], Tokyo, Japan, May 1995.)

10.2.2 Performance Codes

Performance fire safety codes as opposed to prescriptive codes now form the basis of many fire safety designs, especially for big or unusual buildings. Essentially this means using computational analysis over set specifications in the regulations. This process is evolving, and now guidelines have been laid out by SFPE.[4] The guide basically encourages the use of methods that are *verified* and *validated* (V&V). The concept of V&V basically addresses that the ingredients of the method are sound and its limitations clear (*verification*), and the output gives a known level of accuracy against quality data or other valid sources (*validation*). The Nuclear Regulatory Commission (NRC) put forth a report on the V&V of several design approaches to fire.[5] They addressed the equation approach similar to the substance of this book, the use of zone models, and the use of the NIST FDS code. All three methods, where they were applicable, gave comparable and acceptable results for the NRC criteria applied.

Because fire computations require certain expertise, the use of methods, even with a V&V label, does not assure perfection. Indeed, the use of a sophisticated computer model that gives graphical output that looks like smoke and fire can be misapplied, especially when the user only knows how to operate the computer. Tools are becoming user-friendly, and checks and balances must be considered. For a specified regulatory approach, the check to compliance could be done by inspection. For a performance-based design approach the check is not so straightforward. The criteria for design, the analysis in design, and implementation of the design must all be checked in some way. Until this expertise is comprehensive and sound throughout the practice, fire safety design can be problematic. Changing fire safety design from regulations to computers is technologically feasible but may not be practical to implement. Such new technology must progress hand in hand with needed research to fill the knowledgebase and the computer gaps.

My own view is that for special applications performance-based or engineered fire safety designs are desirable. After all this is the basis of engineering. However, in product development, flaws, usually are realized in the engineering stage. Of course, some flaws get by and they are realized in use. The correction of such in-use product flaws is usually well discussed in the public domain. In fire safety, public awareness is usually low. Also fire events that attract sustained public attention are rare. So how can a performance-based design be checked or subjugated to review after a fire event? On the other hand, the current regulatory approach to fire safety lays out specific rules. They are mostly devoid of science, and their basis is sometimes founded in folklore. A historical analysis of specific fire regulations would show scientific weaknesses. A suggestive alternative to performance-based codes is to have an engineering basis for current regulatory specifications. Then the specifications can evolve as science and engineering knowledge improves.

10.3 Fire Investigation

Litigation has pushed the use of computers and fire analysis into the field of fire investigation. In some countries when a significant fire accident occurs, an official board of inquiry is established. Recently, this was done in China for the Mandarin Hotel fire (February 9, 2009). The hotel was 44 stories and was nearing completion when fireworks caused the fire. The building was part of the modern Z-shaped structure of China Central Television (CCTV) in Beijing. Unfortunately, this official investigation will likely never be made public. As with legal litigation, after-incident fire reports are rare or devoid of scientific analysis.

In the United Kingdom, some years ago, the King's Cross subway escalator fire (November 18, 1987) was investigated by an official government board of inquiry. They found through experiments and computer modeling that a fluid dynamical effect caused the fire to lean down against the wooden stairs on the escalator (dubbed the *trench effect*). This close contact with the stairs was deemed responsible for the rapid fire spread. Computer modeling became a forensic celebrity after this fire; however, some still believe that the painted ceiling of the escalator was also critical in causing the rapid fire spread. It is likely to say that the use of computer modeling in the King's Cross fire brought it to the forefront of consideration.

Even before computer models were available, scientists had been drawn into investigations by litigators many years before. As fire research developed models, in terms of formulas, lawyers were astute enough to engage fire scientists. Often, however, litigation never illuminates what happened, as cases are sealed or are confidential. While the King's Cross escalator was of old wood construction, the Mandarin hotel was of modern steel construction. Apparently, something was not considered in the fire safety design of the Mandarin to make it so vulnerable to fireworks. Structurally, however, it survived.

The earliest I recall that twentieth-century fire science tools were used in a notable investigation was the MGM hotel fire in Las Vegas (November 21, 1980). We discussed some aspect of that in Example 1, but those calculations were not part of an official investigation; most modeling was done under litigation. It is likely that sprinklers in hotels and high-rise buildings were required because of the MGM fire.

As in design applications, there is no simple approach to evaluating the fire issues in an investigation without a competent knowledge of fire behavior. Although computer models can be useful, the knowledge gained in this book can go a long way to create a timeline or proposed scenario in a fire investigation. Unlike design, this process for investigation is not open ended. There was a specific fire for investigation, and it did specific damage. These facts must be established through evidence, witness accounts, and analysis.

10.3.1 Dupont Plaza Fire

My experience in fire investigation was nonexistent until Harold "Bud" Nelson and I visited the site of the Dupont Plaza Hotel fire in Puerto Rico (December 31, 1986). Ninety-seven people died, mainly by flame, in the Casino on the second floor of the hotel. The fire began on a first floor of a nearby ballroom among newly delivered furniture. Under auspices of the U.S. Fire Administration and with the permission of the Bureau of Alcohol, Tobacco and Firearms (ATF) Bud and I examined the scene. The unusual aspect of this fire was that the ballroom fire was so fuel rich that when it broke through the glass windows into the Casino, the smoke turned to flame and a wave of fire engulfed the occupants.

We were able to explain this fire and present a quantitative timeline of events by equations very similar, if not identical, to those contained in this book. At that time, Bud Nelson had a computerized rendition of a set of equations called FPETool. Figure 10.4 shows Bud in a pool lounge chair working FPETool with the Dupont Plaza in the background. ATF now has something similar for their fire investigation agents programmed into a scientific calculator. Bud's report can be found through NIST.[6] It was a landmark for investigation showing what a scientific analysis could add to an investigation. The ATF were impressed that we found results consistent with their

FIGURE 10.4
Harold "Bud" Nelson analyzing the Dupont Plaza fire on the scene.

scene and witness data, and we were impressed that we could make this contribution to a real fire.

I can only relate my emotions to the movie, the *Flight of the Phoenix* (1965) in which after a plane crash in the Sahara one survivor says he is an airplane designer and guides them to build a new plane from the parts. On takeoff, they learn that he had only made model airplanes. That is the analogy to Bud and my backgrounds in the laboratory of fire science compared to a real scene fire investigation. Something resonated between the ATF agents on the scene and us. It provided a catalyst to interactions with the ATF fire investigators. Scientists and investigators could learn something from each other. This spirit is making both stronger. The National Association of Fire Investigators has sponsored recent scientific meetings, papers on scientific aspects of fire investigation are appearing in scientific journals, and the International Association of Arson Investigators has a website for knowledge-based learning: CFItrainer.net.

My next involvement with the ATF came in a course we presented to them at the University of Maryland in 1992. Bud Nelson was part of that course. It was a challenge to see if we, as scientists, could present useful information to investigators. Example 3, presented as follows, was a challenge question to see if science could support the evidence of a case being considered by ATF at the time. Later courses with the ATF shaped the first edition of this book.

10.3.2 Example 3: The Case of the Laundry Basket Fire

In May 1993, the murder of a man in Pittsburgh area led to the conviction of his wife with an additional conviction of arson. The wife apparently hatched a conspiracy with an associate to torch her residence, while the family was in Florida. The following gives an account of the events that came to light in the trial.

The wife was accused of masterminding a botched attempt to burn down her home and of filing a false theft report so insurance money could be collected. It came to light in the trial that the woman had devised a scheme to have their house set ablaze, while the family went to Florida. She arranged to have an accomplice torch the residence, while the family was in Florida. But the alleged plan didn't work out. According to a testimony from a county fire official, investigators believe a fire was deliberately set in the basement, but a water pipe joint quickly melted and the water extinguished the blaze in less than 30 minutes. This failed arson event eventually led to the plot to murder the woman's husband, and the subsequent murder trial with the background of a failed arson attempt.

The arson attempt in this was the scenario of fire in a laundry basket that ruptured a copper water pipe, extinguishing the fire. The evidence showed that the fire had been intentionally set between the hot water heater and furnace in the laundry room of the residence. An overhead copper water pipe opened at an elbow joint as the solder connection melted. Plumbing

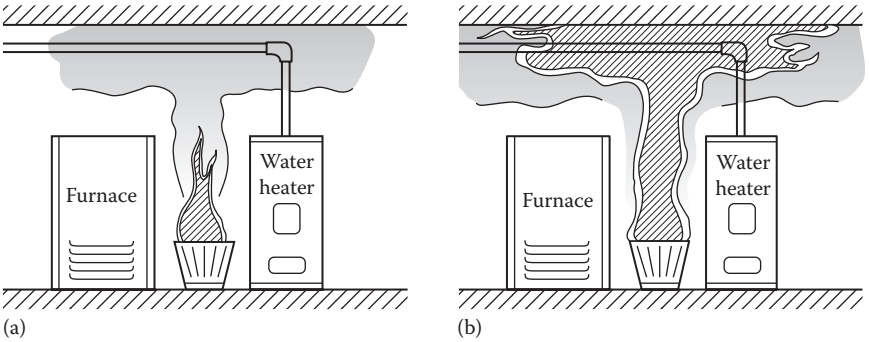

FIGURE 10.5
The laundry basket fire and copper pipe joint. (a) Clothing fire and (b) added gasoline fire.

solders melt in the range of 250°C–300°C at most. To achieve such a temperature, the flame tip of the fire must reach the overhead copper pipe. The flame source must be, at least, capable of this temperature at this height. Moreover, to melt the solder in a water-filled pipe requires the pipe to be bathed in the flame to maximize heat transfer to the solder connection. If the flame immerses the pipe over a length, as the flame temperature is effectively constant, the pipe will have a constant temperature over this length. No temperature difference along its length means no heat loss along the pipe, so all the heat from the flame stays in the pipe. Figure 10.5 illustrates the scenario.

An ordinary laundry basket fire could be approximated as a large wastebasket fire from Table 6.4 as 10 g/s at an estimated heat of combustion of 20 kJ/g (assuming plastic and cotton clothing). This gives

$$\dot{Q} = (10\ \text{g/s})(20\ \text{kJ/g}) = 200\ \text{kW}.$$

From Equation 7.9, we compute a flame height of

$$L_f = 0.23\dot{Q}^{2/5} - 1.02D$$

$$= 0.23(200\ \text{kW})^{2/5} - 1.02(0.7\ \text{m}) = 1.2\ \text{m}$$

where we have assumed a fire diameter of 0.7 m. This flame height, 1.2 m, represents probably an upper limit for a laundry basket fire. But we see that its flames cannot reach the pipe at the ceiling (Figure 10.5a). On the other hand, if an accelerant—say gasoline—were added to the laundry basket, then we have (from Chapter 6) a higher burning rate:

$$\dot{Q} = (55\ \text{g/m}^2\text{-s})(\pi/4)(0.7\ \text{m})^2(43.7\ \text{kJ/g}) \text{ for gasoline}$$

or

$$\dot{Q} = 925 \text{ kW}$$

and

$$L_f = 0.23(925)^{2/5} - 1.02(0.7)$$

or

$$L_f = 2.82 \text{ m}$$

This flame would strike the ceiling and easily bathe the copper pipe joint. Its temperatures would be sufficient to melt the solder (Figure 10.5b).

It should be clear from this example that some choices had to be made on the nature and size of these fires. These assumptions may differ among analysts, but in the end an ordinary laundry basket, even if somehow accidentally ignited, is not very likely to be capable of producing a flame to melt the solder at the joint. Even without any direct chemical evidence of an accelerant, such an analysis would strongly indicate its presence.

The foregoing example arose in the first training course given to fire investigators in the Bureau of Alcohol, Tobacco, and Firearms (BATF) program. Agent William J. Petraitis posed the problem after he and Allegheny County investigator Thomas Hitchings had conducted tests on laundry baskets with and without accelerants. They were looking for telltale fire signatures that might occur. The flame height is the key indicator here. The example proved useful to illustrate the application of the science in this ATF course to a real case. It showed the agents that a calculation could add more evidence to their findings done by tests alone. However, once formulas might lead in a particular direction, if possible, tests should be done for confirmation and demonstrative purposes.

10.3.3 Example 4: An Analysis of the Waldbaum Fire, Brooklyn, New York (August 3, 1978)

On August 3, 1978, a fire occurred at the Waldbaum supermarket in Brooklyn, New York. A sketch of the store is shown in Figure 10.6. At the time of the fire, an extension was under construction as indicated in the figure. The store was a typical supermarket with a mezzanine along a portion of the north wall. The loft was completely of wood construction comprising the floor, roof, and structural support trusses. The trusses were made of 3 by 12 in. members interlaced together in bundles of 4 or 5. Trusses 2, 4, and 6 were covered on one side with plaster to form firewalls in the loft. However, to enable passage, these trusses had doorway openings. The roof

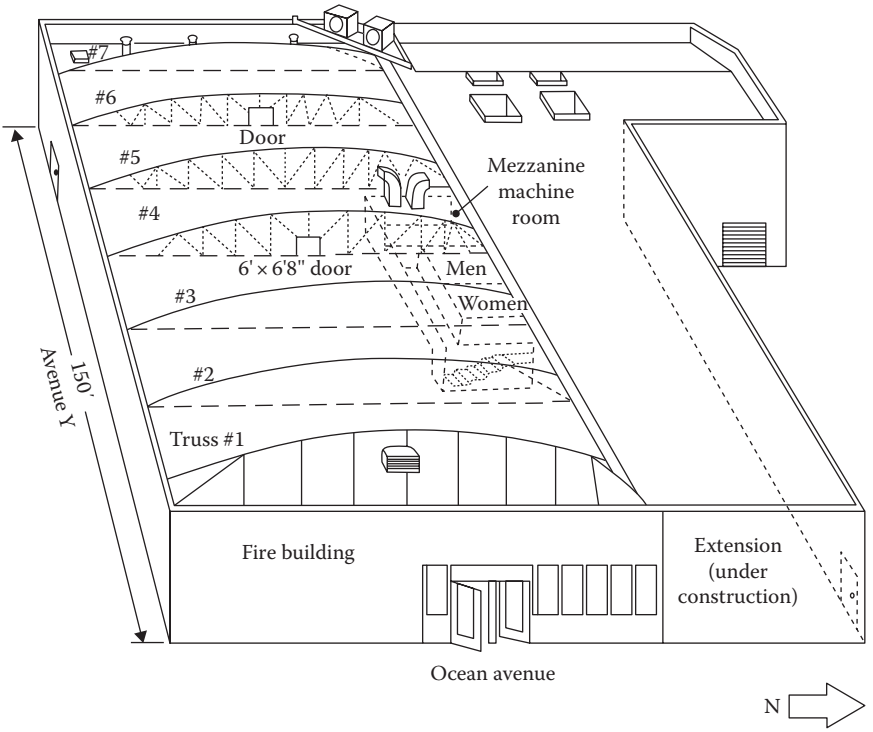

FIGURE 10.6
Waldbaum supermarket, Brooklyn, New York, 1978.

had been modified with a rain roof added at the peak. This construction formed a double layer roof at the peak. Also the new construction required a splayed roof section to meet the new roof of the extension. This construction formed another double roof triangular section along the north wall as shown in Figure 10.7. Due to the ongoing construction and the addition of new columns along the wall to the extension, construction voids existed along this wall to the hidden space between the old and new roof.

On the day of the fire, construction work began at 7 a.m. and the store opened for business at 8 a.m. Flames were first seen at 8:30 a.m. along the interface between the ceiling and extension wall of the mezzanine men's room and the machine room. The fire eventually spread into the loft between truss sections 4 and 6, and collapsed truss 5 at approximately 9:15 a.m. The collapse caused 12 firefighters working on the roof to fall into the flames. Six were killed.

A man was tried and convicted in 1978 of setting this fire. His confession stated that he and two others set the fire near dawn (approximately 6 a.m.) by making holes in the roof and using newspaper and lighter fluid to initiate the

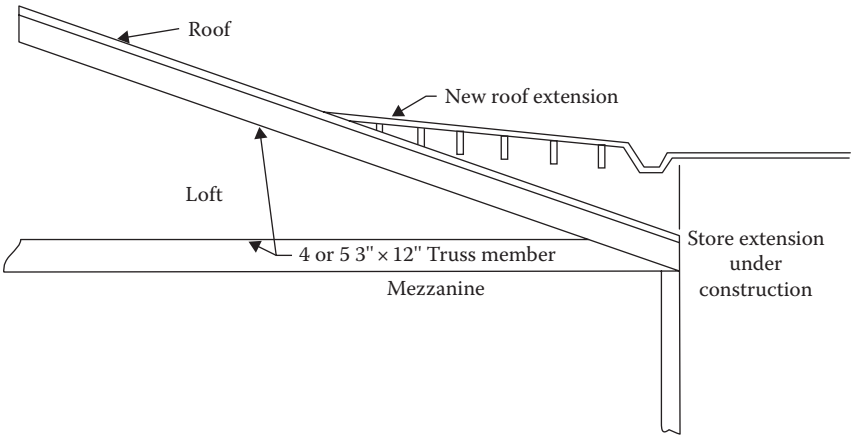

FIGURE 10.7
Splayed roof extension and structural support trusses.

fire below. This confession was later questioned and discounted in a retrial that was held in 1994.

A consistent fire scenario matching the timing of these events was never fully presented. The original fire investigators could not agree on a cause and later suggested that the cause of the fire may have been of electrical origin. However, there was no electrical power in the ceiling area where flames were first seen. Also a workman in the loft, at the onset of the flames to the mezzanine, saw no evidence of fire in the loft. The prosecutors sought advice on how to explain an alleged fire could start at about 6 a.m. but not seen until 8:30 a.m.

I was asked to assist William J. Petraitis, special agent of the BATF in the investigation of this fire, 16 years after it occurred. Agent Petraitis discovered the splayed roof extension, shown in Figure 10.7, and reasoned the fire had to have begun in that space. We then examined the hypothesis of the fire beginning there at approximately 6 a.m. to see if it could be consistent with the other known events. A fire scenario was developed, and calculations were examined to support the plausibility of the events and their timing. All of the analysis is not presented here, but the main results are described. The analyses were performed using the material in this book along with information from the scientific literature. The fire scenario involved issues of ignition to flaming, extinction, smoldering, reignition to flaming, and the burning of wood members to the point of collapse. Here is the proposed scenario supported by calculations.

10.3.3.1 Early Dawn: Ignition (Approximately 6 a.m.)

At approximately 6 a.m., an intentional fire is considered to have been set in the roof area adjacent to the construction of the building extension (Figure 10.8). Based on the original confession, this fire is set by stuffing

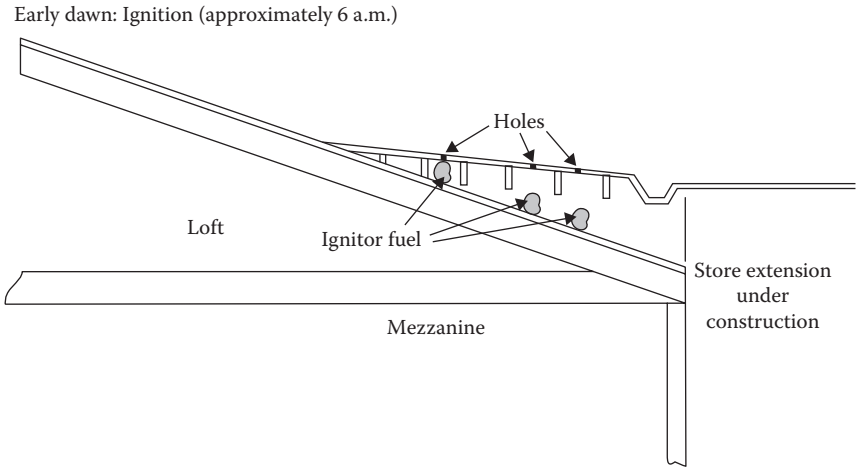

FIGURE 10.8
Flammable liquid-soaked newspapers inserted into roof holes.

paper through holes in the new roof extension along with a liquid accelerant. The splayed roof extension built over the existing roof forms a void space between the two roofs. The new roof is supported by rafters. The fire is set in channels of the wood rafters that extend between the primary wood trusses 4 and 5. Gaps under the rafters allow air to flow into the fire, but the space is mainly enclosed with temporary partitions at the wall adjacent to the new building extension. The accelerant-soaked paper probably caused a fire of 100–500 kW in one or more rafter channels, involving no more than 1 m^2. This fire condition is depicted in Figure 10.9.

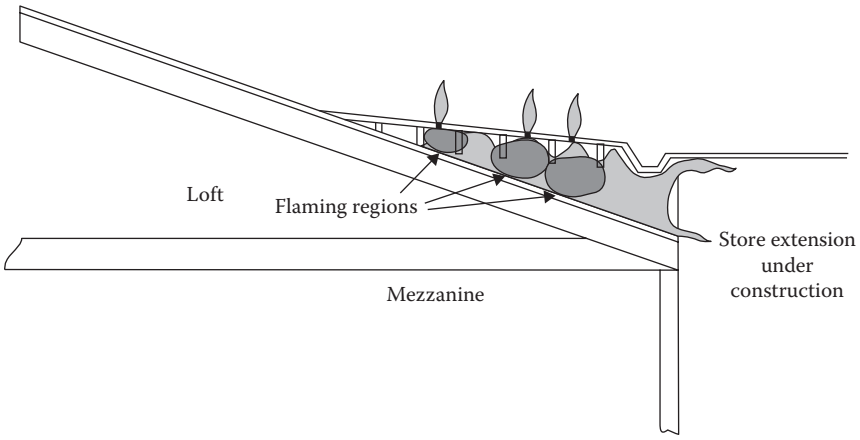

FIGURE 10.9
Ignition at approximately 6 a.m.

Under expected heat fluxes of 40–50 kW/m^2, the wood members would ignite in 30 seconds to 1 minute and begin to contribute roughly an additional 500 kW. The accelerant newspaper fire would burn out in 1–2 minutes. The wood fire could progress to roughly 1000 kW, but then it would become limited in further growth by smoke filling this confined space and consuming its oxygen.

10.3.3.2 Smoldering Stage

Oxygen depletion would cause flaming to cease in about 1–2 minutes following the ignition of wood construction. However, sustained smoldering would be possible, especially in the smaller more confined rafter spaces where radiant heat transfer would be high (see Figure 10.10). Ohlemiller[7] reports that sufficient radiant heat transfer is necessary to sustain smoldering in wood cavities. He also reports smoldering propagation rates of 1–6 cm/h. Using the smaller value, smoldering can propagate through the old 3/4 in. plank roof in roughly 2 hours. A short time before 8:30, a hole would form between the loft and the roof cavity. With air velocity increased to 25 cm/s, Ohlemiller[7] found smoldering in wood would change to flaming combustion. Such velocities would be realized at the hole as air was naturally induced to flow from the loft through the hole into the hot cavity space. Flames would then erupt in the false roof cavity space. Airflow from the loft through the hole would initially keep flames and smoke out of the loft. So here we have a plausible scientific explanation of how a 6 a.m. fire initiation finally breaks out into the loft 2½ hours later. Again, the student should realize that this analysis does not give absolute precision in the timeline,

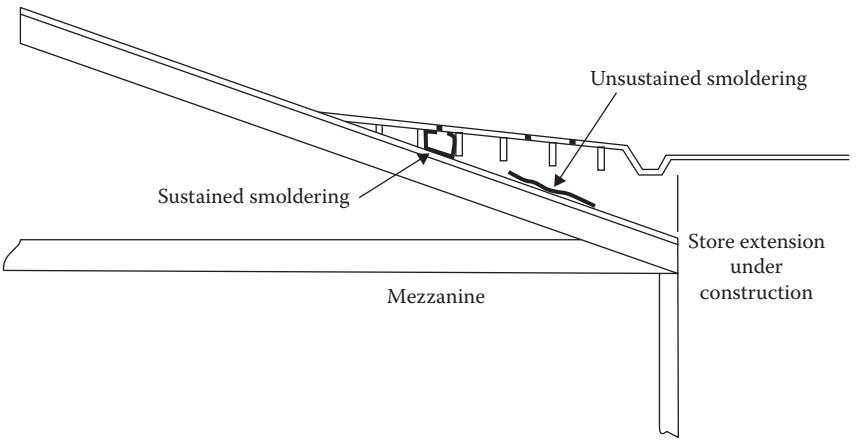

FIGURE 10.10
Smoldering combustion at approximately 6:05 a.m.

but an order of accuracy to within tens of minutes. The estimated timeline agrees with the actual events to *within a reasonable degree of scientific certainty.*

10.3.3.3 Onset of Flaming: Shortly before 8:30 a.m.

At approximately 8:30 a.m., flames are observed in the mezzanine area at the wall and ceiling near truss 4. It is believed that this was due to the expansion of the flames as flashover caused a rapid rise in energy release rate and a pressurization of this confined space (Figure 10.11). The associated pressure increase forced flames through any voids from the cavity space. As the hole to the loft became larger, the increased airflow rate into this hole would also promote a larger flaming fire in the rafter spaces. The flow of the flaming combustion products would follow the rafter channel to the end points at trusses 4 and 5. The first flames in the loft were seen at an opening near truss 4. As the hole to the loft became even larger, flames would lap upward under the sloping wood ceiling of the loft. The person who had been in the loft just before 8:30 would not have been aware of the fire until smoke and flames emerged from the larger hole. In fact, he only saw flames when he descended to the machine room after being warned of the fire.

Evidence to support this stage of the scenario is shown in the photograph of Figure 10.12. The small white vapor plume rising from the roof indicates a hole in the roof. This hole is unlike the larger roof holes, attributed to the fire fighters in ventilating or from burn through of the roof. These large holes emanate dark gray smoke. Flames are also seen to have emerged from the roof on the other side of truss 4. This flaming region is likely just above the first and highest hole made by the arsonists into the confined rafter space as shown in Figure 10.8. Smoldering would have been sustained in this more

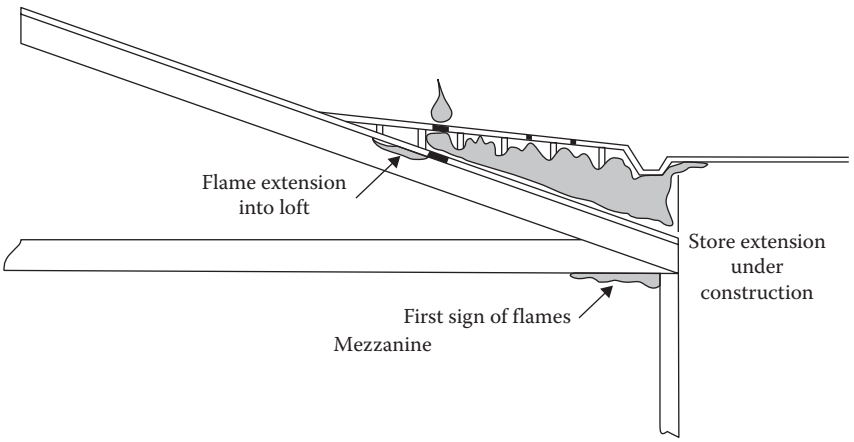

FIGURE 10.11
Flaming erupts in the roof cavity shortly before 8:30 a.m.

FIGURE 10.12
Fire on the roof of Waldbaum store before collapse. (From Hughes, B.J., Private communications of statements and records, Office of the District Attorney, Kings County, Brooklyn, NY, 1994.)

confined space. The hole indicated by the white vapor plume is in the area of the larger void space where fire was likely initiated, but smoldering was not sustained there due to less severe heat transfer.

10.3.3.4 Fire Growth in the Cockloft

Flame spread would rapidly move from the hole, up and under the loft wood ceiling. It is estimated that flames would move from the hole region up and along the peak of the loft to truss 4 and through truss 5 in about 2–3 minutes. This time was estimated from a flamespread model[9] using an ignition time of 30 seconds and an energy release rate per unit area of 150 kW/m^2. Such calculations are beyond the information presented in Chapter 5, as a solution to a differential equation is needed. However, the spread model is based on the theories explained there. This rapid spread (Figure 10.13) seemed incredulous. With the low confidence in flamespread calculations, an experiment was performed in a similar but smaller loft. Flashover occurred in the loft in approximately 1 minute. In the store loft, flashover was estimated to occur when the wood fire contribution was 6–12 MW in the section of the loft between trusses 4 and 6. The flame spread calculation indicated that this would occur in approximately 2½ minutes. So the estimates from the theory are not so different from the smaller loft experiment.

Full involvement was estimated to take up to 5 minutes more. From the onset of flaming at the hole, full involvement of the loft section would take approximately 5–10 minutes. Because of the false roof sections and the truss plasterboard firewall sections, the firefighters on the roof would be unaware of the raging fire in the loft section below them.

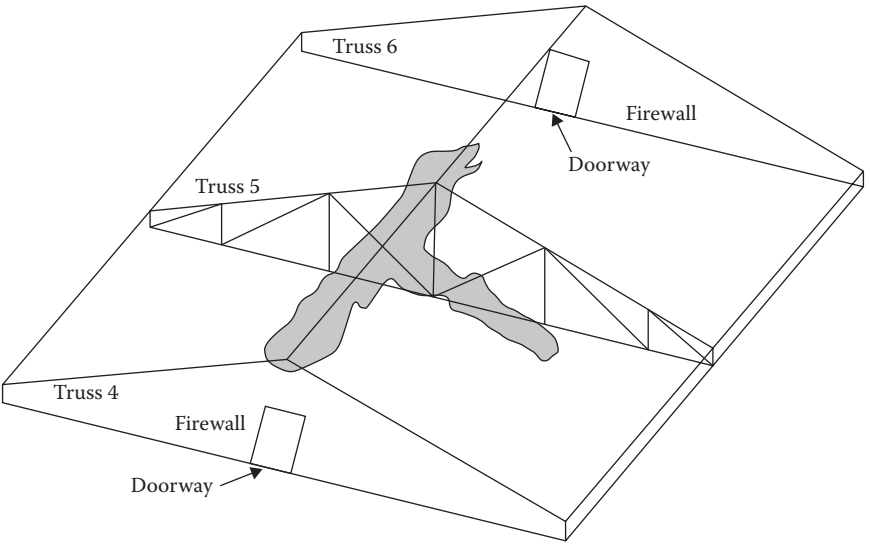

FIGURE 10.13
Fire growth in the loft at approximately 8:35 a.m.

10.3.3.5 Collapse of the Roof due to Truss Member Failure ~ 9:15 a.m.

If one assumes that the roof collapse is due to the failure of a truss member as a result of fire degradation, the burn-through time of a member can be estimated. A fully developed fire in the loft space occurs at about 8:40 to 8:45 a.m. This fire exposure would give the wood its maximum burning rate. From Table 6.2, a mass burning rate per unit area of 11 g/m^2-s is selected as typical for wood under these conditions. For a 3 in. thick truss member, for an estimated density of about 500 kg/m^3, a burn through (1½ in.) would take about 29 minutes. Collapse occurred at about 9:15 a.m.

10.3.3.6 Concluding Remarks

This fire scenario was a complex series of phenomena that are not usually appreciated in the study of fire. Experienced fire investigators at the time of this event in 1978 were not able to deduce this process. Yet relatively simple scientific analysis could produce a plausible and consistent series of events within the periods of the recorded observations of this fire. Some may question the details, but the scenario fits the timeline of what is known and alleged. Only accuracy to the order of minutes is scientifically supported in this analysis, yet the estimated times are comparable to the real events as they are known here.

The photograph in Figure 10.12, which shows the small white smoke plume in the lower right below the bottom edge of the flames, is a telltale indicator. It would appear to be one of the original ignition holes where smoldering

was not sustained in the splayed roof structure. But for a hole above, the fire went from flaming to smoldering and back to flaming. The low rate of downward flame spread kept the fire in the vicinity of the upper hole, but the more rapid upward spread drove the fire into the loft with tremendous speed.

This scenario cannot be described or defended without a comprehensive knowledge of fire behavior and available data to support the calculations. Smoldering research and data are rare but were critically needed in this analysis. The background of this fire was provided by the Office of the District Attorney, Kings County, Brooklyn, New York.[8]

Even if the student cannot perform or confirm all the calculations in this analysis, the qualitative aspects should be generally supported by the subject matter of this book and hopefully the student can accept them. First, the set fires in the roof cavity go out without a sufficient supply of air, but in wood, they can resort to smoldering. Smoldering in wood needs good heat transfer to be sustained and that was realized in the narrow section of the new roof cavity space. Then as smoldering burned through the wood roof into the loft, new air brought the fire to flaming again. As these flames entered the underside of the loft roof, the fire spread quickly into the loft section. Flashover in that section led to a powerful fire with high heat flux that attacked the beam structure causing it to burn through and collapse. This is the basic scientific description of this fire and explains a timeline that extended over several hours.

10.3.4 Example 5: The Branch Davidian Fire near Waco, Texas (April 19, 1993)

This fire involving the Branch Davidian compound near Waco Texas in 1993 was a notable tragic event. The siege preceding the fire brought the attention of the world to this standoff between the U.S. government and a religious group. The siege was prompted by an abortive raid by the ATF for guns acquired by the Branch Davidians. Deaths on both sides occurred as a result of the raid. The siege followed and lasted for many days until the fire.

The opportunity to investigate this fire was afforded by ATF support that allowed Dr. Fred Mowrer and me to join an assembled team of fire scene investigators at the site shortly after the fire. A forward-looking infrared (FLIR) video recording by an aircraft was key to the early investigation in identifying the locations of the initiated fires. Our involvement led to a report to ATF that was later sent to the Department of Justice (DOJ) by the ATF. The fire investigation played out over an extended period of years as various investigations and trials took place. Initially, there was a criminal trial on the deaths of four ATF agents. This trial was followed by a Congressional hearing on the role of the government in the fire and the use of possibly pyrotechnic tear gas. A civil action by the surviving Branch Davidians then led to a trial in 2000. A Special Counsel report by John Danforth to the DOJ summarizes many of these events and states "…what is remarkable is

the overwhelming evidence exonerating the government…".[10] What is also remarkable is that criminal action by the local government having jurisdiction did not investigate the fire for arson nor attempt to hold any individuals accountable. My involvement is summarized chronologically as follows:

- April 22, 23, 1993 Visit scene of the fire that occurred on April 19
- April 25, 1993 Visit FBI headquarters to obtain video and photographic data
- September 8, 1993 Report to AFT and DOJ
- February 1994 Testified in the criminal trial
- July 1995 Testified to Congressional panel
- July 2000 Testified in the civil trial

The scene after this fire was a burned out flattened pile of debris, ash, and horribly, bodies too. Many Branch Davidians lost their lives, not in the fire but by gunshot wounds intentionally inflicted. The nature of the scene is depicted in Figure 10.14. It is clear from that scene that "fire pattern" analysis suggested by fire experts for the Branch Davidians on the fire would not be applicable. The key evidence of this fire was visually documented by both the government and the news media as the compound burned. That evidence and later testimony by surviving Davidians confirmed that the fire started at several locations within the compound. The analysis of that evidence could be amplified by scientific analysis. Some fire events could even be used as

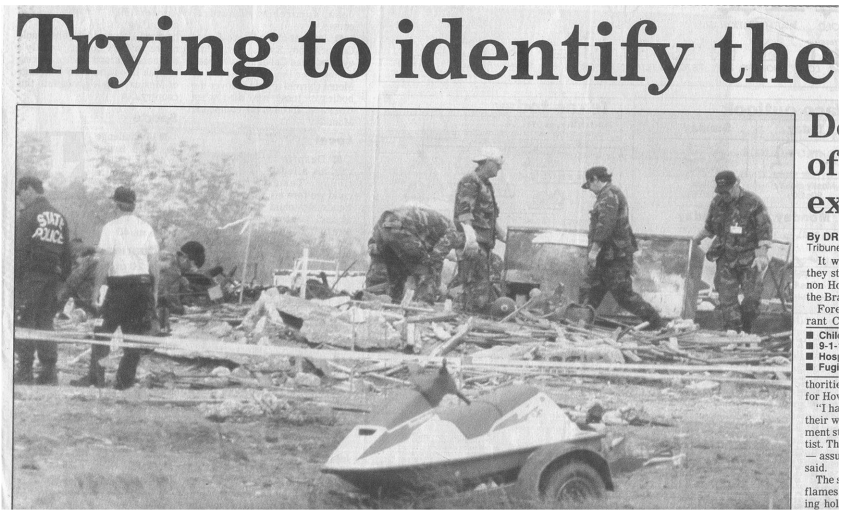
Trying to identify the

FIGURE 10.14
The fire scene at the Branch Davidian compound after the fire. (From *Waco Tribune-Herald*, Waco, TX, August 24, 1993.)

data to cross-check with predictions for scientific correlations. I will relate the story of this fire in scientific terms and illustrate a few analyses.

It is rare that data are recorded during a fire where investigators have a continuous visual documentation of what took place. Because of the circumstances of the siege at the Branch Davidian compound near Waco, Texas, in 1993, much video and photographic recording equipment was being used. The news media were recording video approximately 1–2 miles from the compound, and the government authorities had overhead surveillance aircraft shooting still photographs and a precise time-coded near-infrared video (FLIR) camera. Because of the thermal sensitivity of the FLIR, it easily recorded the fire inception. From these video data, the information in this text, and the behavior of fire, it was possible to reconstruct the characteristics of this fire.

10.3.4.1 Congressional Committee Statement on the Mount Carmel Branch Davidian Fire (April 19, 1995)[11]

A summary of the results was contained in testimony before the Congressional Subcommittee on Crime of the Committee on the Judiciary, and the Subcommittee on National Security, International Affairs, and Criminal Justice of the Committee on Government Reform and Oversight. That testimony is reproduced here, as it lays out my role, analysis of the fire, and my conclusions. The figures used to annotate that testimony have been labeled to agree with the book text. The civil trial later brought some new information to light that confirmed and added to support to these conclusions. For orientation it is useful to recognize the nature of the compound through a scale model of the building, shown in Figure 10.15; and a schematic of the state of the building just before the fire with areas demolished by government activity indicated.

10.3.4.1.1 Background

My name is James Quintiere. I am a professor of Fire Protection Engineering at the University of Maryland, College Park, MD. Before coming to the university, I was a division chief in charge of fire research at the Center for Fire Research of the National Institute for Standards and Technology (NIST). I have 25 years of experience in fire research, education, and in the science of fire growth. I am currently the chairman of the International Association for Fire Safety Science, a world organization of scientists and engineers for the promotion of fire research and its beneficial applications.

Shortly after the fire of the Branch Davidian compound at Waco, Texas, on April 19, 1993, I was asked to contribute to the fire investigation. In doing so, I enlisted the support of Dr. Fred Mowrer, also of the Department of Fire Protection Engineering, University of Maryland. We visited the Waco fire site during April 22, 1993. At that time, we joined the team under Paul Gray

FIGURE 10.15
Scale model depicting the state of the building before the siege.

(Houston), which also consisted of Thomas Hitchings (Pittsburgh), William Cass (Los Angeles), and John Ricketts (San Francisco). The group under Paul Gray would focus on the cause and origin of the fire. We would analyze the development of the fire and draw interpretations and conclusions from that analysis.

10.3.4.1.2 Visual Data

The fire had completely leveled the compound so that no significant structural remains were available to establish the development of this fire. However, this fire was probably one of the most extensively recorded fires in history. Not only were commercial television stations continuously recording this event, but surveillance government planes were taking still photographs and using a FLIR video. These visual records became the principal source of data for our analysis.

The video and photographic data were made available to us by the FBI. Video copies of data that we requested were given to us at the FBI Headquarters in Washington, DC, on April 25, 1993. Subsequently, the FBI video and photo laboratories supplied additional materials and support as requested during our investigation. The data included television coverage of the fire by the Canadian Broadcast Corporation, Channel 10 of Waco, the FLIR video recording, and aerial photographs. These covered the time period of the fire, approximately 12:00–12:30 p.m. CDT.

The principal source of data to establish the inception of the fires and their locations is the FLIR video. Based on the calibrated clock of the FLIR, the other video and photographic records could be correlated, and a comprehensive visual record of this fire could be established. From this visual data, I was able to determine the point of origin of the fires, the growth rates, and estimates of the fire energy output rates at critical transition points in their development. I also drew conclusions of the nature of the ignition sources, the role of the tear gas, the effect of the wind, and the survivability time of the occupants. I will summarize these conclusions and how they were determined. In addition to this statement, I would like our official report and a video I made for the criminal trial to be submitted for the record of this hearing. If you wish, I can review the video as well.

10.3.4.1.3 Ignitions

At least three separate fires began in the compound on April 19, 1993.

Fire 1: The first began at 12:07:42 p.m. CDT in the front of the second floor right tower. This is believed to have been a bedroom. We can expect the furnishings to be indicative of a crowded bedroom. I counted about seven mattress box springs remains in the fire debris at this general location, presumably from this and adjoining rooms.

The precise time of the onset of this fire can be determined because of the characteristics of the FLIR camera. The FLIR camera records the intensity of light and heat radiation in the wavelength range of 8–12 μm. This is in contrast to what our eye sees, which is in the range of 0.4–0.7 μm. As a result, the FLIR operated on auto-ranging, which would set the center of its black and white shading, or gray scale to the ground temperature (say roughly, 81°F). Then it set its range 40° above and below this mid-temperature. As an object in the field of view emitted more radiation due to a temperature increase, the object would appear more white on the IR video. For an 81°F midrange temperature, this would mean that a change from gray to white color would indicate a temperature increase to 120°F or higher. Reflected sunlight could also cause white images, and the FLIR could penetrate smoke; but as the smoke became hotter and thicker, it would see it as white smoke. The FLIR sensor would become saturated at 194°F, above which the image would not be distinguishable. Consequently, the FLIR could detect, by a color change to white, temperatures as low as approximately 160°F (±30° due to auto-ranging). And, it could see through much of the early light smoke of the fire that would obscure the building by normal viewing. The FLIR is the definitive key to the detection of these fires about to start in the building configuration as shown in Figure 10.16.

The image of the temperature rise of the first fire is seen in Figure 10.17, in the second floor south corner bedroom. The first sign of this temperature rise was seen at 12:07:42 in the front side of this room. The image in this photograph occurred 9 seconds later and is due to the transport of hot gases within the room.

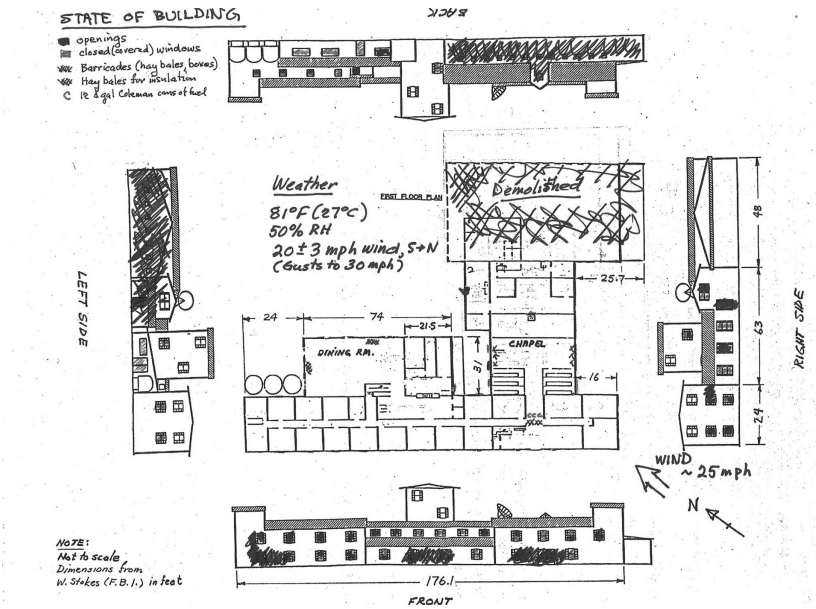

FIGURE 10.16
Schematic of building following demolition action before the fire.

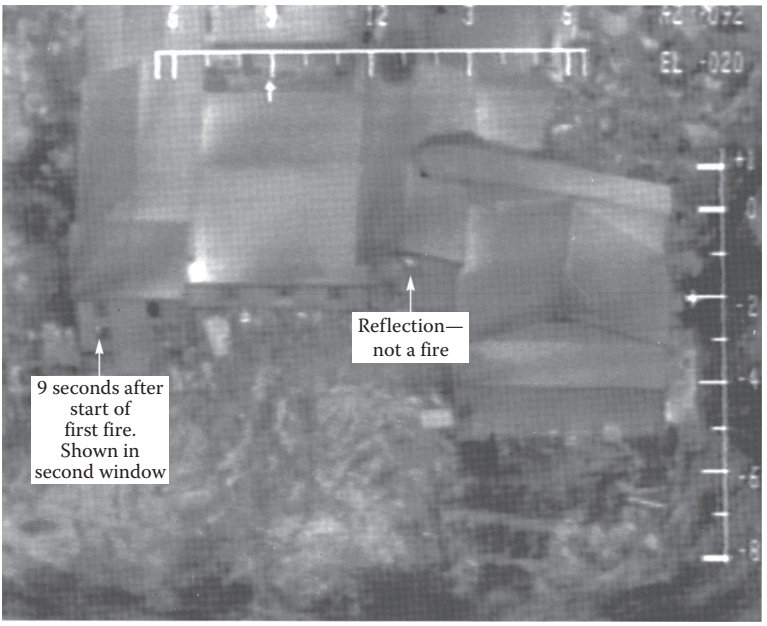

FIGURE 10.17
FLIR image 9 seconds after fire is seen in the second floor south bedroom. A white heat image is seen at the corner of the window.

In a similar manner, the other fire starts were determined. It appears that they all began on the perimeter of the building.

Fire 2: The second fire began in the dining room on the first floor level, approximately 1 minute after the first fire, at 12:08:48 p.m. CDT. This is seen on the FLIR video by a hot plume rising from the rear of the dining room. On surveying the fire debris, I counted 20 burned stacked chairs in this general location within the dining room.

Fire 3: Nearly one minute after the dining room fire began, the third fire is seen in the chapel window on the right side of the building at 12:09:45 p.m. CDT. This is shown in Figure 10.18. The dining room fire is also visible, and the bedroom fire has now affected adjoining rooms, adjacent, and above.

Less than a minute later, a related or separate fire is seen to occur in the debris area behind the chapel at 12:10:23 p.m. CDT, as shown in Figure 10.19. This fire could have been connected to the previous chapel fire. The time difference between the two fire observations is comparable to the time associated with flame spread on a liquid fuel poured between the two points.

Figure 10.20 shows an aerial view at about the time of the possible fourth fire start. By comparing this figure to the previous figure, it can be seen

FIGURE 10.18
FLIR image showing hot (white) region at the first floor chapel window indicating the start of the third fire.

FIGURE 10.19
FLIR image showing possible fourth fire start in debris area behind the chapel.

FIGURE 10.20
Normal photograph showing smoke obscuration of the compound.

that the visible smoke is much more evident than in the FLIR image of Figure 10.19. This figure shows the advantage of the FLIR in being able to see through this smoke.

10.3.4.1.4 Flashover

Following ignition of these fires, the next significant event is flashover, which marks the transition point of a discrete fire in a room to a fully developed fire in which flames now fill the room and emerge from the windows. It is rapid and can take place in seconds. It occurs after the room is sufficiently heated. It marks the difference between survivable and nonsurvivable conditions in that room. These events can be seen, directly and indirectly, from the video records. The first is seen directly for Fire 1 as shown as window flames appear in the split screen images of Figure 10.21.

Flashover occurs at 12:09:42, 2 minutes after the start of that fire. Calculations show that this fire growth rate for the initial burning item would be rated as "fast" according to NFPA standard 72E. Its energy release rate would be about 2 MW at flashover, compared to an estimated 50 kW that was necessary for detection by the FLIR. The detectable fire is like a 1 ft^2 spill of gasoline, compared to a 10 ft^2 gasoline fire at flashover.

Fires 2 and 3, in larger rooms, grow much more rapidly than the bedroom fire. Flashover occurs in about 2.5 minutes for the dining room (12:11:07) and in 4 minutes for the chapel (12:13:49). Figure 10.22 shows the effect of flashover for the chapel by black smoke that suddenly emerges from the front opening in the building. This smoke, pouring into the 25 mph wind, is due to the overpressure caused by the sudden increase of energy associated with flashover in the chapel.

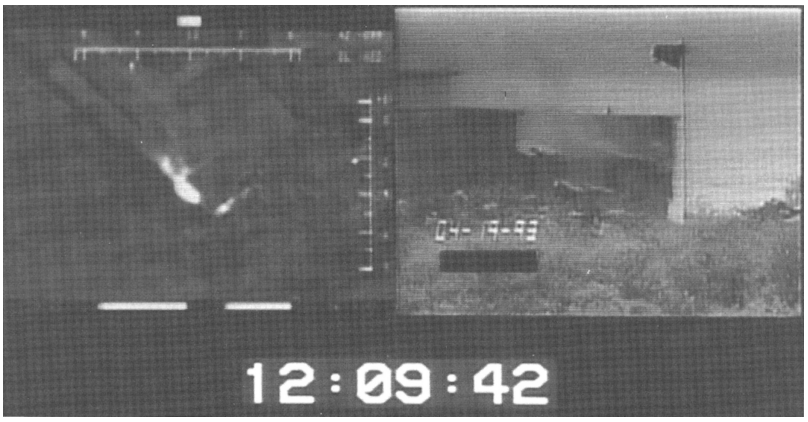

FIGURE 10.21
Split screen showing a comparison between a FLIR image and a normal video image at 12:09:42.

FIGURE 10.22
Black smoke is pushed out of the front (right) opening as a result of flashover in the chapel.

10.3.4.1.5 Fire Cause

It is concluded that these three fires, occurring nearly at 1 minute intervals, were intentionally set from within the compound. Even if the tank battering had caused the spillage of fuel from lamps, a match would be needed to initiate the fire. An electrical spark is ruled out because the electric power was shut off in the compound. It is obvious that these three fires needed an ignition source deliberately placed in each of the three locations. Also, none of these three fires could have caused any of the others because their growth rates would not provide sufficient heating to cause such remote ignitions. Any external heat source that might have been used to start the fires would have clearly been visible on the infrared video. This heat source was not seen. Although normal furnishings and interior construction characteristics would provide a means for fire propagation, the more than usual rapid spread of these fires, especially in the dining room and chapel areas, indicates that some form of accelerant was very likely used.

10.3.4.1.6 Tear Gas

Methylene chloride, used as a dispersal agent for CS tear gas (2-chlorobenzalmalononitrile), is flammable as a vapor at a concentration of 12% in air; however, it is not easily ignited as a liquid. In fact, it will put out a match on attempting to ignite the liquid. Although fire spread was relatively rapid in the compound, these rates are not indicative of the much

more rapid propagation that would be associated with a flammable mixture in air. Those rates would be in excess of 2 ft/s and would be seen as a fireball moving through the atmosphere of the interior of the compound. No such characteristics were observed in this early fire growth.

Recently, I conducted additional experiments to access the role of methylene chloride as a wetting agent to available fuel types in the compound, such as wood and paper. Since methylene chloride is a liquid at normal temperatures, it could have been absorbed into the furnishings of the compound. From my experiments, I can conclude that the methylene chloride had no enhancement effect on the fire spread over room furnishings. Also, I can conclude, from the flashpoint data (197°C or 387°F) of CS itself, that its deposition on furnishings should not have had a significant effect on fire propagation either. The tear gas had no bearing on the propagation of this fire.

10.3.4.1.7 Wind

Wind effects did have a profound effect on the external fire spread over the compound. An approximate 25 mph wind from the south caused the fire plume to be bent approximately 65° from the vertical when the fire fully involved the compound. It is estimated that the fire was expending 3600 MW at this time with an observed length of approximately 240 ft.

Wind effects did not appear to have had a significant effect on the fire growth within the compound, as seen in Fire 1 where flames and smoke emerge periodically from the right tower windows into the wind. This effect could have been as a result of closed doors or windows on the downwind side of the compound. The tank-made openings on the front of the compound could have had some effect on fire growth over the first floor, but more significantly could have provided air to areas of refuge for some of the occupants.

10.3.4.1.8 Survivability

It is estimated that the occupants would have had sufficient warning of the fire to enable them to escape, for at least up to 5 minutes from its inception, and up to nearly 20 minutes in some more protected locations. This is dramatically indicated by one occupant who jumps from the second floor 12 minutes after the start of the fire. Although smoke would have impaired visibility, exits were within 30 ft of most occupants, with additional openings made by the battering tanks.

Carbon monoxide in the smoke would have been the primary threat to the occupants. However, preliminary autopsy reports made available to me indicated that only 5 of 31 victims with recorded CO levels had lethal levels of carbon monoxide (CO). The remaining 26 victims, with recorded CO data,

stopped breathing before lethal CO levels were attained. If these data are correct, at least 26 victims did not die due to the fire. The autopsy report goes on to indicate that, in at least 27 of the victims, the cause of death could be attributed to gunshot wounds.

10.3.4.1.9 Concluding Remarks

During the weeks preceding the fire at the Branch Davidian compound, we were all bystanders to the drama of the standoff and wondered how it would end. The eventual outcome was a horrible event. In the 2 years since, many theories about the fire have been proposed; some quite bizarre. I hope this presentation, our report, and the video I would like to submit will help explain the events of this fire.

10.3.4.2 Follow-Up to Waco

Following that testimony, I thought that was the end of my involvement. But in August 1999 I was retained by DOJ to serve as a fire expert in the civil trial of July 2000. New information came to light. I will not go into it all. But one event struck me: the rescue of a Branch Davidian woman who jumped out of the second floor window 12 minutes into the fire. She then crawled back into the flaming first floor, only to be reluctantly rescued by the heroic action of a FBI agent. That section of the building collapsed in flames several moments later. While the rescuing FBI agent was internally recognized, I do not think that action received any outside publicity. Indeed, an immediate criminal investigation of the fire in 1993 never emerged. It was as if the entire event should be forgotten. Of course, for some, it was only an inspiration that led to the bombing of the Alfred P. Murrah Federal Building in downtown Oklahoma City exactly 2 years later on April 19, 1995. That bombing was the most destructive act of terrorism on American soil until the 9/11 attacks.

10.3.4.3 Scientific Analyses of Some Aspects of the Waco Fire

Let me conclude the story of this fire with some excerpts of analyses that illustrate the use of science. In some cases the illustration may not have been critical to the conclusions of the fire. Consider the following phenomena.

10.3.4.3.1 Fireball

At about 19 minutes from the onset of the first fire, while the compound was nearly completely covered in flames, a large fireball was seen, as shown in Figure 10.23.

FIGURE 10.23
Fireball occurring in the midst of Branch Davidian fire.

From Chapter 7, the equations describing the dynamics of a fireball are given as (here the units have been changed from cm to m)

$$\text{Height of fireball: } L_b \text{ (m)} = 12.7[V_f \text{ (m}^3\text{)}]^{1/3} \tag{7.23}$$

$$\text{Maximum diameter: } D_b \text{ (m)} = 7.7\ [V_f \text{ (m}^3\text{)}]^{1/3} \tag{7.24}$$

$$\text{Burn time: } t_b \text{ (s)} = 2.8\ [V_f \text{ (m}^3\text{)}]^{1/6}. \tag{7.25}$$

From the video records and from length scale estimates, the corresponding results were estimated:

Maximum diameter about 22 m
Height about 38 m
Duration about 3 seconds

The consistency and accuracy of the formulas can be examined. By combining Equations 7.23 and 7.24, a diameter is computed to be 23.2 m when using 38 m as the height. The observed maximum diameter is 22 m as estimated from the visuals. Using now 22 m for the diameter, the duration is computed

to be 4.7 seconds compared to 3 seconds from the visual records. Moreover, accepting 22 m as the diameter, the volume of fuel released can be calculated as 23 m^3. As it was believed that the fireball was the result of a breached propane tank into the fire, taking the density of propane in normal air to be 1.82 kg/m^3, the mass of propane released is 42 kg or about 93 lbs. This is consistent with a 100 lb capacity tank. There was such a tank outside the building where the base of the fireball appears to originate. This is quite a remarkable confirmation of equations developed in the laboratory using much smaller scale data.

10.3.4.3.2. Wind Effects on the Flames

A curious phenomenon in this fire was that flames exited the window directly into the wind at the corner room of Fire 1. The wind was nearly continuous at about 25 mph into that corner of the building as depicted in Figure 10.20. The only way that could happen is that the door to the fire room on the second floor was closed, or the second floor corridor had limited ventilation. This means that the room is being pressurized by the wind, and the flow acts like normal buoyancy-driven flow with a neutral plane at the window. A flow analysis of the effect of wind and demolition penetrations to the building was done and concluded this bidirectional flow of smoke and air on the wind side of the Fire 1 room was supported as long as it was closed from the second floor corridor.

For Fire 2 on the first floor in the dining room, the flow analysis predicted that wind would blow through the large demolition hole at the front of the building and then out through voids in its rear wall. Indeed, flames were seen penetrating this rear wall. In addition, this flow analysis indicated that the wind would push the fire in the chapel area (Fires 3 and 4) toward the demolished gym in the rear. While these effects explained aspects of the fire and supported their behavior and timing, a calculation of the overall wind effect on the building's flames was not so critical to the investigation.

However, another calculation showed the accuracy of a scientific formula. Equations by Thomas for wind-blown flames developed for wood cribs of a finite width give the length of the flame and its angle as a function of the wind speed and firepower.[12] These equations were applied to the building when flames completely engulfed it. The flame angle from the visual records indicated it as about 65° from the vertical. For that angle and wind speed, the Thomas equations indicated a fire of about 4000 MW and a flame length of 64 m. The visual record showed a flame of about 80 m long. This is quite a consistent result, with again small laboratory-based formulas giving credible results in real fires.

10.3.4.3.3 FLIR Result

The FLIR was key to this fire in identifying the precise timeline and the location of the fires. In addition, together with the media coverage, the

indication of full fire involvement could be discerned for the compartment in which each fire originated. Hence, an indication of fire growth rate could be determined. Analysis showed that the characteristics of this FLIR would allow a visibility through the early gray smoke of the fire at 17 times what normal human sight could discern. In addition, the FLIR would indicate a gray spectrum that moved from a black image to white for temperatures of about 8°C–56°C, respectively. This meant that in viewing the first fire from the aircraft height, the floor through the open window would be in view and when it indicated a white image the floor would be about 56°C. This level of temperature would result from a fire very early in its growth and would be small. Following this event, flames were seen to emerge from another window of the room some distance away in about 2 minutes later. In this way, the growth rates of all the fires could be determined.

An interesting estimation of the growth rates of these fires (1–3) was determined in terms of the *t*-squared growth time to reach 1000 kW (1 MW), as explained in Chapter 6. The FLIR and other visuals could allow the time at inception and the time of flashover by indications of full room involvement. From the room size and its ventilation openings, the firepower at flashover could be estimated from Equation 9.10. Assuming that these fires grew as *t*-squared fires, then this information could be used to calculate the growth rates in that format. Figure 10.24 gives the 1 MW growth times for the three fires and compares them to other fire growth rates, as given in Chapter 6. It is clearly seen that these separate distinct fires occurring in the Branch Davidian compound were relatively very fast, and that speed of growth makes them suspicious and not accidental. The addition of ample liquid fuels in the compound and evidence given by surviving Branch Davidians indicating the fires were purposely set makes the scientific results compelling.

10.3.5 Patterns

Patterns in fire investigations have long been an indicator for drawing conclusions. This *pattern analysis* for fire investigation begs a scientific basis. Yet relatively little research has been exercised. Many have come to realize that such indicators as the spalling of concrete or the deep charring near an open door do not necessarily mean arson and an accelerant. The student should recall that many liquid fuels, in particular gasoline, have low boiling points. At those temperatures, a wood floor would be protected, while the liquid is still burning. Of course, some type of pattern may emerge, but this needs some research to make any discriminations. The damage of spalling in concrete is due to water trapped in the concrete and stresses caused by boiling and also by thermal stresses alone. These stresses break the concrete sometimes in a violent fashion. They are caused by the high heat flux in rooms that go to flashover.

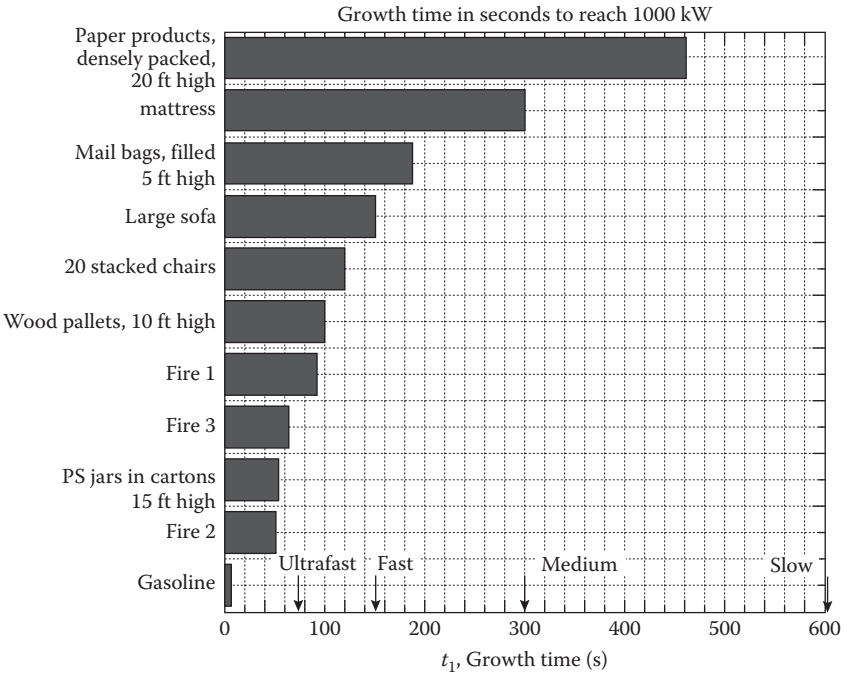

FIGURE 10.24
Fire growth rates in terms of time to reach 1 MW by a *t*-squared rate.

Speaking of *flashover,* there seems to be confusion among investigators on what it is. Many claim no flashover occurred in rooms that are damaged and charred throughout. Perhaps they are working from a different definition of the term. We should recall *flashover* is a transition of the fire from an object or discrete region burning to a fully developed fire controlled either by ventilation or by the fuel in the room. That accelerated transition is flashover. Its end result produces much damage and of course patterns. We now know that ventilation-limited conditions can cause the fire to seek out the sources of air. Hence, deep burn damage near ventilation openings occurs.

In the end, fire leaves patterns and they may have forensic value, but this process must go beyond the reading of tea leaves. Let me introduce some ideas on patterns from cases or fire experiments that I have experienced. In some instances, they are hypotheses that need research.

10.3.5.1 Soot Patterns

We know that soot is produced on the fuel side of a diffusion flame, and in turbulent flames, it will break out of the flame and move away with the smoke.

As it is born by a given fuel, it may carry a chemical signature of that fuel. I know study on tracing the soot chemistry to the fuel has been done in China. Maybe this will be a fruitful path for forensics someday. Let us look to the physical nature of soot.

The deposition of soot on surfaces commonly occurs in fire. It can occur due to turbulent impaction and settling due to gravity. However, the main mechanism for its deposition is *thermophoresis*. This process is stronger than turbulent diffusion alone. It is a process where soot particles move from a high to low temperature. The mechanism is much like heat moving from high to low temperature, but in this case the soot particles move too. In the early stage of a fire, when the surfaces are cooler than the smoke, the soot deposits by thermophoresis. Later, as the surfaces heat up, or the fire dies, little more soot is deposited. In the area of the early fire before flashover, the flames may strike a wall. But we know from Chapter 7 that about 10 times more air than needed to burn the fuel is entrained into the flame. This means the hot turbulent flame is rich in oxygen. As the flame strikes, the wall where soot is deposited, the high temperature and availability of oxygen can now burn the soot. Hence, a *clean* burn mark can occur on gypsum walls as the soot is burned off. Now as the fire moves to flashover, and ventilation effects take the flames away from this area and its oxygen drops, the clean burn pattern can survive the fire, especially if suppression intervenes.

10.3.5.2 Clean Burn Pattern

Figure 10.25 shows the onset of a bedroom fire experiment at a clothes-basket against a gypsum board wall. The aftermath of that fire involving the full bedroom and into the rest of the house leaves a *clean* burn where the fire began. This is common in fire experiments as such a clean burn can be definitively traced to the origin area. The oxidation of steel to rust might be another indicator of early fire growth. These indicators need

FIGURE 10.25
Bedroom fire leaving a *clean* mark on the wall at fire origin.

study to confirm and identify their meaning to fire growth. As we know after flashover the flame can move about the room in a ventilation-limited fire. This can produce additional clean burns as the soot is burned off. If this hypothesis is correct on the formation of clean burns, then the clean burn farthest from the room vent is likely to be at the origin of the fire.

10.3.5.3 The Hands of Time in a Fire

An unusual pattern occurred in a scenario of a sofa fire in a small apartment. Because no doors or windows to the outside were open or broken during the fire, the apartment filled with smoke and consumed the oxygen to a level where the fire went out. The fire was set to cover up a murder in the apartment. A man was later tried and convicted. A curious aspect of this fire was the soot on a clock in which, for lack of a glass cover, indicted a clean image of the clock hands. The clean image on the clock indicated a time for which the convicted man could not have set the fire.

To investigate this further, a fire experiment that mimicked this apartment scenario was conducted. It was prompted by the way thermophoresis causes soot deposition. In the experimental fire, that had nearly the same volume as the apartment fire, the fire began on a sofa at 11:20 and extinguished from lack of oxygen at 11:25. Its smoke barely reached 300°C, and the soot was strongest just before the fire died. Several open-faced clocks were placed on the walls of the room. They all gave similar patterns exemplified by the photograph in Figure 10.26. The hour hand's clean image clearly indicates a time of 11:20–11:25. It points to the initiating time of the experimental fire.

Initially, as the fire on the sofa began, the clock was cold and the soot deposited. The fire grew and consumed the oxygen, and then died. When it died, the clock was now at a higher or equal temperature to the smoke. No more soot gets deposited. As the temperatures never got high enough to destroy the clock workings, the clock continued to run.

In the murder case, a similar clock image was left on the functioning clock. Its cause was never traced back to the nature of thermophoresis.

10.3.5.4 Gasoline versus Fire Damage

In another case involving alleged arson and murder, a man was convicted and recently died in prison. Guilt or innocence is not the question here, but the nature of the evidence and its interpretation by experts in the trial are important to examine.

One expert reported that burn patterns in the living room, dining room, and kitchen were indicative of the use of a liquid accelerant. Core samples of the concrete floor in the living room revealed the presence of gasoline. The investigator determined that the fire had been intentionally set.

FIGURE 10.26
Clock hand image due to soot deposition in a fire began at 11:20 and died at 11:25.

This investigator also eliminated the possibility of a *flashover* as having occurred in the apartment.

An expert for the defense claimed that the fire started in the kitchen on the stove and then spread to the living room as a result of a flashover. He testified that the burn patterns on the living room floor were the result of a normal fire and that the gasoline could have been in the concrete long before the fire.

I came into this fire by a civil case and was drawn to the background of the murder conviction. In my opinion, the fire began in the kitchen and flashover surely occurred. Indeed, this fire spread into the hall and other apartments in the building. The apartment of origin had a fully developed ventilation-limited fire that had to pass through flashover. The kitchen had the most damage, but that alone is not sufficient to tag it as the origin. The telling bit of evidence is that the kitchen had no windows. For the fire to have originated in the living room from gasoline, with an open door to the hall and sliding glass doors broken by flames to the patio, means that the flames would move first out of these openings. Then later it would move back into the closed confines of the kitchen as the fire burned out in the surrounding areas or as fire suppression would

intervene. The kitchen would have less damage than the living room and the intervening dining room. But the kitchen had the most damage, and that could only occur by a fire originating there. Its only source of ventilation was the rest of the apartment, and as the fire became ventilation limited, the flames would move from the kitchen through the apartment to the openings.

The extreme disparity in opinions by these investigators is troubling. One relied on a gasoline signature and claimed flashover never occurred. The other was unable to articulate that the kitchen damage was due to ventilation effects on fire behavior. An underlying question is whether a chemical signature of a liquid accelerant always indicates arson.

10.3.6 World Trade Center Terrorism and Fire (9/11)

We all remember the day of September 11, 2001. We all know the cause of the fires that brought down the twin towers. Two commercial Boeing 767 airplanes traveling over 500 mph struck each tower. The North (WTC 1) hit after the South (WTC 2) fell in 102 minutes and the South in 56 minutes. Later fires in WTC 7 fires by falling flaming debris caused it to fall in about 7 hours. The question of interest to designers and investigators should be why such notable buildings would not have the inherent fire protection to sustain these fires and not cause them to catastrophically fail. Let us take a look at this question.

The WTC twin towers were constructed in the 1960s with a unique design to open the floor. They might be characterized as a steel "tube" construction. Its central core columns took most of the gravity load with sharing by 59 perimeter columns that were mainly to handle the wind loads. A "hat" truss at the roof allowed for load sharing among the perimeter columns. The floor system between the perimeter frame and the central core consisted primarily of a concrete metal deck supported by a double truss (bar-joist) network, 900 mm deep, with web rods of 27.7 mm (1.09 in.) diameter that spanned to 18.3 m. The main trusses were cross-braced by similar secondary joists. The entire floor truss system was aligned by bolts and welded to seat connections at the perimeter and core columns. Figure 10.27 shows a plan view of a typical floor with overall dimensions of the open office and core spaces along with its structural design aspects.

In an early design analysis, a calculation considered the effect of a Boeing 707 traveling at 600 mph hitting a tower. It concluded that it would only cause local damage and most certainly not total collapse. This was confirmed by the slightly bigger 767 planes that hit the two towers; they did not fall under impact. Of course there was structural damage, but it was the long burning fires that eventually weakened the steel structure. Why? A lot has been said on these issues since; perhaps more study is needed.

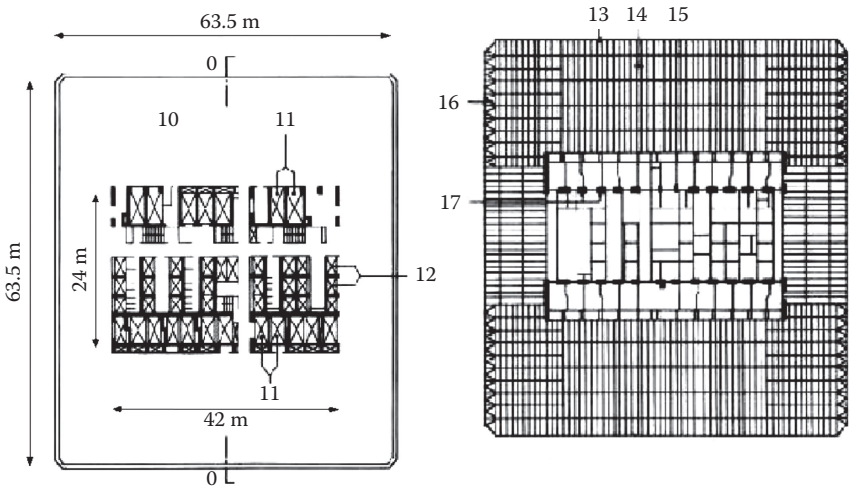

FIGURE 10.27
Plan view of typical floor and structural design (number labels: 10—office, 11, 12—lifts, 13—perimeter frame, 14—bar joists, 15—secondary joists, 17—core columns). (From World Trade Center building performance study, Federal Emergency Management Agency, FEMA 403, 2002; Quintiere, J.G. et al., *Fire Safety J.*, 37, 2002.)

10.3.6.1 Investigative Efforts

A terrorist attack on the United States fell under the jurisdiction of the FBI on 9/11. While ATF had a mandate to investigate federal crimes of arson, and National Transportation Safety Board investigates air crashes, they were not enlisted to conduct any official investigations. The American Society of Civil Engineers (ASCE) sent a voluntary team to the WTC site. Later they were funded by Federal Emergency Management Administration (FEMA) and produced a good first attempt at the cause.[13] Nearly a year after the attack on the buildings the federal government funded two investigative actions: (1) the 9/11 Commission[14] and (2) NIST.[15] The latter organization was to focus on the fires and building collapse, while the 9/11 Commission focused on all other aspects. The Commission was eventually funded at $12 million and completed its work by a mandated constraint in 2 years. It held many formal open hearings with witnesses under oath. The NIST investigation finished its report on WTC 1 and 2 four years after the event in 2005 with initial funding of $16 million. They produced a 10,000-page report. The result took longer than the U.S. involvement in World War II and cost about $1600 per page or more. With added funding, NIST completed a report on WTC 7 in 2008. In contrast to the Commission, NIST held open workshops to display progress and allowed visitors 5 minutes for formal comments and allowed no questions.

Two books by NY Times reporters are very illuminating on the WTC event. The first by Glanz and Lipton[16] addresses the development of the WTC buildings up to their collapse. The second by Dwyer and Flynn[17] portrays, in riveting fashion, the actions of those in and around the buildings on 9/11.

I got involved in the investigation in a very nonofficial way. I was not enlisted in any part of its official investigation or in litigation. I did get an offer from the ATF agents at Federal Law Enforcement Training Centers (FLETC) in Georgia to drive through the night with them to the Pentagon on 9/11. I was about to teach a course on fire dynamics. Instead I opted to fly back the next day. Alas, all airports were shutdown, and they opted to stop and sleep in Motel 6 that night. I spent about a week waylaid in Tampa, FL.

The ATF only remained at the Pentagon site for several days and were not requested to go to NYC. Meanwhile, I settled into business, and learned I had been volunteered for the backup ASCE team. I never went to the site, but I soon learned that the steel was being carted off to the dump with no attention to forensics. I was appalled. As I spoke out, I attracted the attention of the Skyscraper Safety Campaign founded by Sally Regenhard and Monica Gabrielle, who were members of the *9/11 families*, losing a son and husband, respectively. They were bent on determining the cause of the collapse. And they were instrumental in their crusade in securing the NIST funding from Congress.

First, drawn by curiosity to see if the formulas of fire science could shed light on the collapse, we published a paper.[18] I enlisted the assistance of Dr. Rachael Becker of the Technion. She had studied the fire resistance of steel structural members and the role of its insulation. In 2000, she had been a guest worker at NIST and in our department at University of Maryland. We could only do a sketchy job, having no full information. Later I went deeper as the information from the FEMA report became available,[19] and finally, I published a document challenging aspects of the NIST investigation.[20] I will not go into all the details, but I will take you to places where formulas and information in this text can lead you to make your own analyses.

Recently, NIST published the results of the WTC investigation in a peer-reviewed journal. This opened their analysis and conclusions to public comments. After a Letter to the Editor of the journal was redacted beyond recognition, it was submitted instead to another fire journal. The authors of the Letter were myself and Professor F. A. Williams, a noted combustion scientist who had served on the NIST WTC advisory committee.

In short, our conclusion is that the bar-joist floor trusses failed due to lack of sufficient insulation as specified in the design; NIST concludes that the trusses had sufficient insulation and that the aircraft dislodged critical insulation on the core columns and allowed them to weaken by the fire. The reader can examine the *Comments* to NIST and their *Response* in the Forum section of the *Journal of Fire Sciences*.[21]

Now, let us examine some aspects of this event in terms of formulas discussed herein, and factual information supported from References,[19,20] and in general from the FEMA[13] and NIST reports.[15]

10.3.6.2 Role of the Jet Fuel

Many laypeople today believe the jet fuel played the dominant role in the fires. It was the igniter, but not the fuel for the fire of long duration. On impact, fireballs erupted. There were about three or four emanating from the sides of a tower. Anyone can find a dramatic photograph of this event and then scale the size of the fireballs. We have in Chapter 7 a formula that relates maximum diameter to initial fuel volume. Making an estimate of the bulk density for the fuel in the dispersed spray at the impact, the fuel burned in the fireballs can be determined. From Chapter 7: D_b (m) = 7.7[V_f (m^3)]$^{1/3}$ and with an aerosol density of 2 kg/m^3 gives about 1000 kg burned in a single fireball. Considering four fireballs, that is, 4000 kg burned outside. Each aircraft carried about 10,000 gal of jet fuel or about 28,500 kg. The remainder of the fuel, about 24,500 kg, burned in the building. The maximum burning rate per unit area for JP-4 is taken as 60 g/m^2-s from Table 6.2. Over a single floor of office area of about 3000 m^2, this results in about 181 kg/s. This means that the jet fuel could burnout if just spilled over one floor in 136 seconds (24,500 kg/181 kg/s). It likely takes longer due to ventilation and transient burning effects, but the result clearly indicates that the jet fuel is short lived. If a spill over several floors is considered, less fuel per floor means even a shorter burn time. By all accounts, and confirmed in the NIST analyses, the jet fuel is the starter only. Indeed, it acted as the igniter and an extensive enough igniter to eliminate the normal fire-developing phase of traditional building fires. Hence, it can be concluded that large fully developed fires immediately occurred on the impacted floors of the towers.

10.3.6.3 Fuel Load for the Fire

Now, the question turns to what *did* burn. In this case, it is the contents of those floors impacted and set on fire by the jet fuel. NIST concentrated on reconstructing the fuel load of the Marsh McLennan offices struck in WTC 1. They used the same fuel load for the trading floors struck in WTC 2. From Table 9.2, the average fuel load for an office building is 39.2 kg/m^2, but with large a standard deviation of 34.7 kg/m^2. NIST obtained an estimate for the Marsh McLennan space in the WTC from architectural drawings. I was able to obtain the same from a *9/11 Family* source. Kate Stewart, a student at the time at Maryland, who was very skilled in building plan review, examined the plans and computed a load. She contacted the furniture suppliers for their weight information, estimated transient materials in a typical office, and discovered NIST did not include a ring of common metal file cabinets. She computed the furniture load without the common files

at 61,054 kg compared the same furniture computed by NIST at 60,643 kg. This gave us confidence in our accounting methodology. There were 170 4-drawer files left out by NIST. We computed with only 50% paper capacity in the files that they constituted another 75,000 kg per floor. So the NIST analysis used a fuel load of 19.5 kg/m^2 of flow area, while we think there was at least 44 kg/m^2. NIST apparently only used the architectural drawings as their source information. I talked to people who had been on the Marsh McLennan floors before the fire. A manager told me they were paper hogs, and a security guard said that stacks of paper covered the windowsills. Some at NIST told me paper does not burn in the file cabinets. So I did a test with a file in a furnace at typical fire temperatures; after 2 hours about 60% of the paper was consumed with only ash and char remaining.

The importance of the fuel load in an investigation of fire involving structural damage is that the duration of the fire and its temperature control the response of the structure. The longer the fire, the more vulnerable is the structure. Let us make a rough estimate here. In Table 6.2, the maximum burning rate of wood cribs per floor area (they sit on) is listed at 11 g/m^2-s for burning in the open. Assuming the furniture and paper burned as a crib fire, the NIST fuel load would give a fire burning time of 0.48 hours (19.5 kg/m^2/0.011 kg/m^2-s). Our larger estimate gives 1.08 hours. Ventilation effects would make these estimated times longer, and we know the fires lasted on a floor for up to the collapse time of WTC 1 at 102 minutes. The importance of the fuel load should be clear, and relatively simple estimates can indicate the duration and temperatures in the fire.

10.3.6.4 Fire Effect on the Structure

In the case of a steel structure, it must not exceed 500°C–600°C, as its strength diminishes dramatically at those levels. Indeed, this temperature level is usually a criterion of failure in standard furnace tests. These furnace tests subject a particular structural element with its applied insulation to a severely increasing temperature and then rates its failure point by time. When the World Trade Center was built in the 1960s, the required rating by such testing was relaxed from 3 to 2 hours. Most tall buildings built around the world today require 2 hours. Many argue that the standard furnace tests do not represent a real fire, but the test temperatures typically achieve 600°C quickly, 800°C in less than ½ hour, and 1000°C in less than 1 hour. The WTC fires are surely represented by these temperatures. So the rating by standard tests has some meaning in reality.

Good engineering practice would be to first determine the fuel load of occupancy, estimate its burning time, and specify a rating in hours for the structure that exceeds the burning time. This can be done by formulas, computer modeling, or by test data. This would be the performance design approach. Usually, regulations require a rating, and for the WTC, it was 2 hours for the floor trusses.

Something unusual happened in the life of the WTC towers. The required insulation on the steel truss rods of the trusses of about 1 in. in diameter (27.7 mm) was changed. How this happened never came out in the NIST investigation, but it is known that the required thickness was changed in the mid-1990s, nearly 30 years after the towers were built. This change was implemented as floors became available due to changing tenants. The change made was to increase the original specification of ½–1½ in. of thickness for the spray-on insulation. Apparently this was changed on examining recently tested structures representative of the WTC trusses. Why such testing on the actual structural elements was not done in the design of such an unusual building is unknown.

The NYNJ Port Authority (PA), responsible for the WTC, did inspections of the sprayed on insulation. Their reporting to NIST indicated that the original ½ in. specified was about ¾ in. applied, and the 1½ in. was more like 2¼ in. applied. NIST used the applied levels in their calculations. I used ¾ in. in mine but stuck with 1½ on the change, as I found it difficult to believe that a spray-on company would add so much more. The PA specified amount would result in a 4 in. diameter, while the applied PA amount would have a diameter of 5½ in. No photographic evidence of the newly applied insulation was ever presented in the NIST report.

Here is the punch line to all of this. The Marsh McLennan floors in WTC 1 had the newly applied insulation to the trusses. The fire area of the South tower (WTC 2) had the original insulation. It is simple to wonder if WTC 2 had ¾ in. and WTC 1 had 1½ in., then WTC 1 might fall in twice the time. Well, WTC 2 fell in 56 minutes and WTC 1 fell at 102 minutes. Indeed, I will leave you with the results computed in Reference[19] using formulas for to predict the time the steel rod of the truss would achieve a failure point of 600°C with the different amounts of insulation. The formula accounts for conduction through the insulation with all of that heat to uniformly raise the temperature of the steel. The fire temperature is nearly the temperature of the outer insulation, as the heat resistance of the insulation dominates the heat transfer from the fire to steel. The calculation specified the fire temperature at 800°C, likely low for this fire. A heavy core column was also included, and the effect of losing the insulation was examined. Table 10.1 gives a summary of the results for the different truss rod insulation thicknesses and also a core column.

It can be seen from Table 10.1 that the computed times for the trusses at the fire floors of WTC 1 and 2 give times consistent with the collapse of the buildings. The calculations support the fire as the cause of the collapse. The failure of one rod is manifested as the sagging of the trusses over the floor. The connections at their ends cannot tolerate this new loading configuration with the steel in a fire-weakened state. As the connections fail, the floors begin to fall in total or in part. In the Glanz and Lipton book,[16] they cite observations of "sudden smoke puffs" out of the fire floors up to 10 minutes before total collapse of the buildings. I interpret this as local floor failures. As one or two floors fell on to the next, the connections at the truss ends were

TABLE 10.1

Heating Times for Structural Elements

Element	Insulation Thickness mm	Insulation Thickness in.	Time to Reach 600°C with Insulation (min)	Time to Reach 600°C with No Insulation (min)
27.7 mm steel rod	12.7	½	55	8
27.7 mm steel rod	19.1	¾	73	8
27.7 mm steel rod	38.1	1½	111	8
55.8 cm box column with 7.6 cm thick steel	28.6	1⅛	1640	75

Source: Quintiere, J.Q., A predicted timeline of failure for the WTC towers, in: *Proceedings of the 10th International Conference on Interflam 2004,* Interscience Communication, London, U.K., 2004, pp. 1009–1022.

not strong enough to carry the weight even for unaffected fire connections. A domino effect resulted.

10.3.6.5 Afterthoughts on WTC

In any investigation, one cannot know if truth prevails in the conclusions. It is interesting to observe that the NASA Columbia mission fell to Earth in February 2003, and its accident report was concluded in August 2003. This was a fire too; the insulation protecting the shuttle on reentry was damaged on launch. Scattered debris, flight evidence, recording evidence, and definitive tests concluded the cause was the damage at launch. In the TWA 800 crash (July 17, 1996), a fuel tank fire was found to be its cause. It took a reconstruction of the debris raised from the Atlantic Ocean to piece back the evidence for supporting its cause. In both cases, actions were taken to prevent accidents in the future. NASA revised its launch procedures with attention to the effects of foam insulation on the cryogenic fuel tanks; the aircraft industry developed fuel tank inerting systems. In the case of WTC, the NIST conclusion was that the impacting aircraft dislodged key insulation on the core steel columns, and the insulation specified on the trusses was sufficient. So while NIST made many recommendations for improvement, the issue of the floor truss insulation was not a consideration. Was the insufficient insulation the cause? Why did such a significant building not have more attention paid to its structural fire protection? Why the changes in the insulation? Why the discarding of steel from the site into new products from abroad and memorial artifacts? Why not a reconstruction with the steel from the fire floors (as the primary structural elements were marked to location)? If steel is examined by metallurgical testing after a fire, its maximum temperature reached in the fire could be determined with good accuracy. NIST did this late in their investigation, but having only anecdotal limited steel, the tests were insignificant.

My intent here has been twofold: first to cast doubt on the NIST findings, and second to demonstrate that formulas developed from fire research can produce information even in a complex event as the WTC fires on 9/11.

10.4 Computer Fire Models

Computer models are mathematical solutions implemented and displayed on computers. They attempt to alleviate the user from the direct development of the mathematical solution, and usually make it convenient and easy for the user. In addition, if they are very easy to use, the user may not need to know anything about fire behavior to get a result. The same issue can apply to use of equations for a particular fire phenomenon as given in this book. The user need only know how to compute the algebra. In the end, competency requires understanding of the application as well as skill in implementing the model.

In all models for fire, the models are approximate. There are no exact solutions in the complex area of fire. The mathematics offers an approximate solution to a physical problem, either through an equation or by a computer. In this book, the equations have been developed from theory of the phenomenon, data from or confirmed by experiments, and then the formulation of a generalized formula. In a computer model, these equations may be used as part of the model to synthesize many phenomena together. Alternatively, a computer model may be based on the fundamental equations representing conservation of mass, momentum, energy, and subsidiary equations governing properties and other effects.

10.4.1 Zone Models

The first type of computer model used in fire was a system model, often called a *zone model* because it treats fire in a room as upper and lower zones exchanging mass by the fire plume and at vents (see Figure 9.6). The model by Tanaka et al.,[1–3] and illustrated in Figures 10.2 and 10.3, is representative of a zone model. This type of model is based on fire flows being stratified in a room and on known physics of fire phenomena. For example, a pressure-difference model governs flow at vents, an entrainment model governs flow into the fire plume, heat transfer to surfaces is based on specific equations for convection and radiation, and so on. As more phenomena are known or required, they can be folded into the system model. Sometimes the folding-in involves approximations. For example, the fire is assumed to have no volume in the two zones, but separately its volume can be computed. One may think this is not so good, but a similar technique can be used for calculating drag over an airfoil. The pressure distribution is computed with no regard for

friction in the boundary near the surface of the foil. Then that pressure distribution is used to compute the friction at the boundary.

Such system models are used in many fields, and they give an overview based on the component phenomena that can be mathematically expressed. They form commonly ordinary differential equations in time. Quantities in each zone or boundary are computed as a function of time. The computing process requires the speed and storage capacity of a computer. As its computations only deal with time, it can be a fairly fast process. In addition, such a system model can be extended beyond rooms in a building. One application, illustrated in Figure 5.10, shows how the fire plumes and emitting firebrands from burning wooden houses can be synthesized to model fire spread in a conflagration. In Japan, such an approach has been used to assess the risk of fire to people and buildings in fire following earthquake. A dramatic application has been to model the fire and its effect on people seeking refuge following the Great Kanto earthquake and fire of 1923.[22] A conception of the model is shown in Figure 10.28. The model considers the growth rate of the fire over the houses, the effect of radiation, and convection heat transfer to people moving to areas of lower hazard potential and refuge sites. Statistical factors are also considered in the model.

The accuracy of the model simulation is indicated by its prediction for the number of people reaching the various refuge sites compared to those estimated by a survey taken in 1923. These results are shown in Table 10.2. It should be noted that most of those reaching the Hifukusyo Ato site were killed by the large fire whirl (see Chapter 1).

Zone models are only as good as the system of equations coupled together. Again, the user must look under the hood to understand such a model. The model led by Tanaka[2] is popular in Japan but does not have a wide distribution. A CD disc comes with the original reference that explains the model and

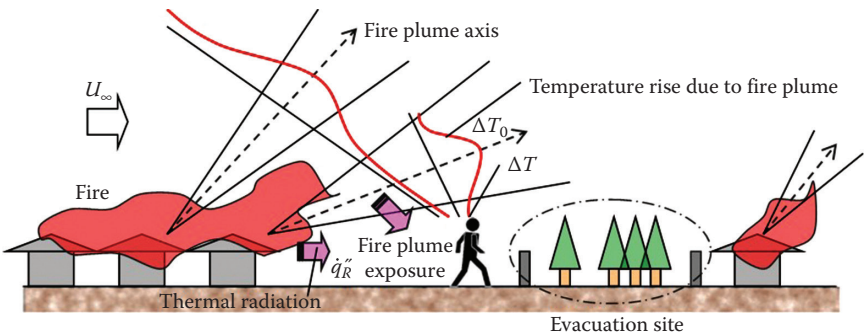

FIGURE 10.28
Model concept for the effect of fire, following earthquake, on people in evacuation to refuge sites. (From Nishino, T. et al., A study on the estimation of the evacuation behaviors of Tokyo city residents in the Kanto earthquake fire, in: *Proceedings of the Ninth International Symposium on Fire Safety Science*, 2008, pp. 453–464)

TABLE 10.2

Number of People Reaching the Refuge Sites in the Kanto Fire

Number of Evacuated Person	Ueno Park	Asakusa Park	Fukagawa Landfill	Hifukusyo Ato	Seicho Park	Imperial Palace Park	Shiba Park	Yasukuni Park
Simulation	174,100	70,880	52,020	40,290	20,010	215,430	56,020	26,660
Survey[3,4,9,10]	500,000	70,000	50,000	40,000	20,000	300,000	50,000	50,000

Source: Nishino, T. et al., A study on the estimation of the evacuation behaviors of Tokyo city residents in the Kanto earthquake fire, in: *Proceedings of the Ninth International Symposium on Fire Safety Science,* 2008, pp. 453–464.

allows for its use. A more readily available zone model developed by Colleen A. Wade, called BRANZFIRE, can be downloaded at http://www.branz.co.nz/cms_display.php?sn=74&st=1&pg=9456. It is a well-supported code.

10.4.2 Field Models

The second type of computer fire model is termed a *field model*. It solves for every point in the domain of the problem and advances the results over time. These field models are generally called computational fluid dynamics models. Usually, they use the fundamental equations of physics and chemistry in an exact mathematical form. The form is partial differential equations in time and three spatial coordinates. The partial differential equations must be solved. They cannot be solved into formulas; they can only be approximately solved by repeated numerical computations. This requires large computers. The first step in this approximate solution is to divide the domain space into finite cells. Then the model predicts temperature and other variables for each cell and steps forward in time over specified increments. The mathematical cell approximates results for ideally each point. The cell size may be larger than phenomena that the model purports to predict. When this is the case, the model must adjust with special provisions. Unfortunately, issues of turbulence and combustion occurring at millimeter scales are not fully resolved; to get them correct requires special models that are not perfect and the subject of continuing scientific development.

A popular fire field model is the fire dynamics simulator (FDS). It is described in literature and can be downloaded from NIST along with the computer code in a user-friendly rendition. It was released in 2000 and is currently being used by several thousand people around the world for a wide range of applications from design to investigation. A review paper on the model describes its limitations and its ability.[23] It cites three issues with such a model of fire: (1) fire has many scenarios, models cannot do all; (2) the computational power of computers is limited, but always improving; and (3) models are needed to predict how real objects burn, and this is not possible today. A big limitation is the ratio of largest to smallest scale that is needed to model all fire phenomena. Fire in a building may need 10's of meters to indicate geometry, and predicting combustion from fundamentals requires a cell size smaller than a millimeter. This requires a ratio of scales, largest to smallest, of about 100,000. To capture all of this range is impossible with current computers. So in the rendition of large building spaces the cell size is practically selected to be of the order of a meter or slightly less to get the code to complete the calculation in less than a day or two. This means that unless phenomena such as combustion that occur at much smaller scales are not dealt with in special ways to insure their accurate prediction, the results pertaining to combustion and other small-scale phenomena can be poor. Despite these limitations such codes can be very powerful in giving a detailed output for the fire and smoke. An example is its ability to compute the turbulent flame shape over intervals

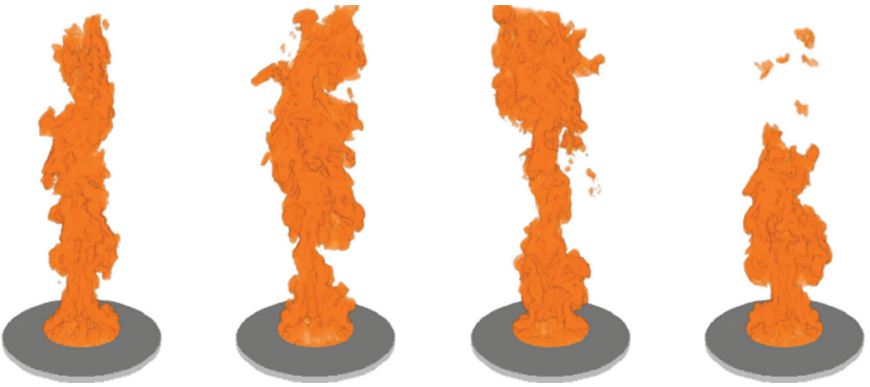

FIGURE 10.29
FDS prediction of a 1-meter-diameter methane turbulent flame. (From McGrattan, K. et al., *Int. J. Comp. Fluid Dyn.*, July 2011.)

of time as shown in Figure 10.29. The model captures the dynamics of the turbulent flame and its oscillatory nature very well. On average, its predicted flame height agrees well with the formula in Chapter 7, and that formula correlates a wide range of experimental data.

Another field model under development is FIREFOAM by FMGlobal. Its goal is to predict commodity fires in warehouse settings and their suppression by sprinklers. Its progress to date has been very impressive.

Modeling of fire by computer is essential to get all of the combined effects of fire. Smoke flow through a building can be modeled, fire growth aspects can be considered, and toxic and thermal effects on people evacuating over time are possible. But all of this must be done with understanding and validation. The user cannot just be skilled at using the computer. This book has attempted to give some understanding of fire and its effects to a student with limited mathematical and scientific training. Today, people with those limitations are likely to be more endowed with computer skills. To them I say, learn and know what you are using when considering fire models.

10.5 Summary

A consideration of fire modeling in applications to fire safety design and fire investigation has been discussed. Generally, fire safety is dealt with by regulations, and equivalency principles allow an alternative with engineering analysis. Performance-based design is being used as an alternative to regulatory specified rules. In a performance-based method, formulas and computer models seek to achieve a safe design based on a quantitative

benchmark. Many of the principles and processes quantitatively described in the previous chapters can be used in various design or investigative problems. In addition to the formulas considered in this book, computer models offer an approach to fire modeling that may require no understanding of fire. It should be apparent to achieve a competent level of fire modeling, and knowledge of the subject needs to be mastered. Modeling by computer or formula needs competency. Several examples of fire investigation were presented including the Branch Davidian fire near Waco, Texas, of April 19, 1993. The examples try to illustrate the approach to investigative analysis and to show that formulas can give credible predictions. In both design and investigation, perfection in prediction is not essential; ballpark estimates are usually sufficient. Predictions in terms of seconds, minutes, or hours, and mm, m, and km are usually good enough to exclude a fire scenario or set limits in design. The example of the Waldbaum fire is a good illustration to show how order-of-magnitude estimates can explain a timeline that extended over hours. The example of the WTC 9/11 events speaks both to issues in design and investigation. Computer models have been discussed in terms of the system-type zone model represented by the Japanese BRI-2 and the field modeling approach represented by FDS.

Review Questions

1. What is performance-based design?
2. Do models need to be verified and validated? What does this mean?
3. What is a zone model? What is a field model?
4. How did the example of the fire in the laundry basket indicate arson?
5. How was the fire from the bombing of the WTC in 1993 different from the fires in 2001?
6. Do fires leave patterns that have meaning?

Activities

1. Consider one or two examples from your fire experience to analyze. Have the class discuss these and work up calculations to quantify features of the fire scenario.
2. Identify computer models sold or made available to the fire community such as FDS and BRI-2. Investigate their contents. Discuss.

3. Identify regulations in fire safety that could be enhanced by analyses. Discuss.
4. What additional aspects of fire safety would you like to see computed? Are these formulas available?
5. Consider each of the examples presented in the chapter. Raise questions, comments, and other calculations to challenge or defend the conclusions.
6. Discuss the investigative approach to the 9/11 WTC collapses and the design of fire protection in those buildings.

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Appendix: Mathematics of Science

Learning Objectives

Upon completion of this section, you should be able to

- Appreciate why mathematics is needed for science
- Be able to perform algebraic operations
- Be able to read a graph
- Know the importance of units and how to convert to SI units

A.1 Introduction

This appendix has been included to provide a brief review and introduction to algebra. It is to help the student with algebraic symbols and operations. In addition, it will illustrate how algebraic equations come about in science. The ability to manipulate equations requires a basis in algebraic principles and the ability to use consistent units for physical quantities. Hopefully, this addition will give the student a better learning pathway to the material in the text.

Science is the organization of knowledge into general laws and principles that apply over a broad range of conditions. For example, on the Earth, rules may apply, but when traveling in space, they may be slightly different. This deals with your frame of reference, geometrically and in time. Albert Einstein showed time can be distorted, while Isaac Newton treated time as invariant. In other words, we might shorten time (and aging) under high-speed interplanetary travel, but on Earth we all age with the same time standard. As we are addressing time mainly on Earth for fire considerations, we do not have to concern ourselves with Einstein's time stretches. However, conditions on the Moon or Mars will subject fire to other gravities, and in an orbiting vehicle no gravity is experienced. Scientists are now studying how to expand the material in this book to those non-Earth-bound gravitational conditions.

A.2 Mass and Energy Concepts

Now let us return to science and only consider the rules that apply on the Earth. First, let us address mass and energy. While these are common terms, they are not easily defined because they are concepts. Yet all matter contains mass and energy. Suffice it to say that mass pertains to a measure of the quantity of matter. Mass can be considered as that amount of matter expressed as weight; weight being the force necessary to suspend an object of matter in the Earth's gravitational field. Energy might be related to the amount of work it takes to raise an object of matter to a higher elevation on Earth. Work itself is a form of energy defined as the weight of the object times the distance it is raised. Work is a very tangible quantity involving a force (weight) and a distance. Energy in general may not be so tangible. It has many forms, and its identification with work can be simply a way to recognize that it is present in some particular form. For example, we might have energy due to motion (kinetic energy) or that due to the flow of electrons in a wire. The modern physicist makes no distinction between mass and energy. Indeed, 1 Joule (J) of energy is equivalent to 1.11×10^{-17} kilograms (kg) of mass. This follows according to Einstein who related them through his groundbreaking equation $E = mc^2$.

Most have heard of this equation and here we have our first scientific law given as an equation. The letter E stands for energy and m stands for mass—this seems logical. And c is the speed of light in a vacuum, 299,792,458 m/s (m stands for meter, and s stands for seconds) to be exact. We might also approximate this large number as 300 million m/s. That is the same as 3 with 8 zeroes following it, or 3 times 100,000,000, or 3×10^8. Einstein's equation justifies why 1 Joule (J) of energy is equivalent to 1.11×10^{-17} kilogram (kg) of mass as

$$m = E/c^2 = 1\ \text{J}/c^2 \sim 1\ \text{J}/(3 \times 10^8\ \text{m/s})^2 = 1/(9 \times 10^{16}) = 1/9 \times 10^{-16} = 1.11 \times 10^{-17}\ \text{kg}$$

If this is not understandable, hopefully by the time you finish this chapter it will be clearer. First we need an appreciation of mathematics in science; then we need to learn how to manipulate equations into solutions.

In the representation of the speed of light, meters per second were used as its measure. Others might prefer different units as 670,616,629 mph (mph is an abbreviation for miles per hour). Ordinary people in the United States would better relate to the mph units, but most scientists use the metric system, or more precisely the Standard International (SI) system of units. Many countries, with the notable exception of the United States, use the SI units in common practice. Now here we see that scientific terms have units, and the units are somewhat arbitrary and vary with tradition and country. But of course, without equivalence between the various units of measure for the same quantity, technological exchange would be impossible. So commerce must rely on precise measurements of mass and energy, and laboratories around

the world ensure that we have standard scales of reference and exact conversions between the various different units of measure.

A.3 Conservation Laws

Back to energy and mass. In $E = mc^2$, we see E and m are related through c^2 (c-squared, or $c \times c$). As c is a universal constant (never changing), it means E and m can be exchanged. Of course, they only can significantly exchange under atomic reactions, as in the atomic bomb where the fission of an atom (a form of mass) leads to a small loss of mass that produces a big amount of energy. This is seen from the formula, as c is a very large number.

A.3.1 Conservation of Mass

Fire deals with chemical reactions only, so $E = mc^2$ will never apply. Chemical reactions rescramble the atoms of the molecules of the reaction, and the original mass of the reacting molecules is the same as the molecules formed. The atoms in the molecules at the start of the chemical reaction and the newly produced molecules at the end remain the same. For example, carbon might react with oxygen and burn to carbon dioxide. If a perfect mixture of carbon and oxygen is introduced (such a mixture is called "stoichiometric"), none of the carbon and oxygen will remain after the reaction. In terms of mass, we might consider this as one atom of carbon combining with an oxygen molecule that has two atoms of the element oxygen. The carbon dioxide that forms has exactly these same atoms in its molecule. These original atoms have not been destroyed in the chemical reaction. The matter in terms of the atoms remains the same. As mass is the general measure of the quantity of matter we say: *mass has been conserved*. This is a general law of nature called the "conservation of mass." By deduction, as all matter has energy as well as mass, we might conclude that there is also a "conservation of energy law."

A.3.2 Conservation of Energy

Energy, however, can take many forms and each has to be recognized and accounted for in applying conservation to energy. For example, an object that is dropped in a vacuum, offering no resistance, will have all of its potential energy converted into kinetic energy. Suppose the object is perfectly insulated and is moving without the aid of gravity in a vacuum and now strikes an immovable plate. The kinetic energy must go somewhere. The temperature of the object will rise, as this kinetic energy is now put back into the matter of the object. The temperature is a manifestation of

the *internal energy* of the object. Thus, the internal energy of the object has increased while its potential energy has dropped an equal amount.

In fire, the chemical reaction releases energy in the form of heat. What actually happens in this chemical reaction is internal energy within the original molecules is converted to a new form of energy (*heat*) as the chemical reaction proceeds. The final internal energy of the molecules that form is less by that amount of heat that was lost to the surroundings. The total energy stays preserved and is redistributed as

Energy of reactant molecules = Heat transferred + Energy of product molecules

The difference between the energy of the reactants and products is the energy lost to the surroundings as heat. Thus, the sum of energies at the end is the same as the energy at the beginning. This is an example of the conservation of energy law. As no atoms were destroyed or converted into energy in the chemical reaction, the mass is also conserved. Only by rescrambling the atoms of the reactants into new product molecules has energy been redistributed.

The conservation of energy is commonly called the "first law of thermodynamics." These laws for mass and energy cannot be proven; they are based on scientific observations of which no exception has been found. Also *energy* and *mass* are invented terms to express these concepts from observation and measurement. Thus, we need to appreciate that science is the generalization of observations into laws that govern the behavior of the universe. We can relate mass to the quantity of matter (stuff), and all mass has energy that can be recognized in various forms. For example, kinetic energy is defined as mass times one-half of its velocity squared. A weight falling a certain distance is said to do *work* and the rate of doing work is commonly called *power*. Water flowing over a dam can be converted from work to kinetic energy of a water wheel that is now spun. But friction robs us of some of this waterpower generated by the wheel. By measuring these different forms of energy, the conservation of energy has been validated. In this way, scientists have built up the identification of many forms of energy and have shown that energy is conserved when it is transformed to a new form.

A.3.3 Conservation of Momentum

There is one final universal law, and it is known as "Newton's second law" (after Isaac Newton) where

$$F = ma \tag{A.1}$$

Here, a is the acceleration of the object mass, m, subjected to a force, F. A mass receiving a fixed force will accelerate according to this formula (law).

Equation A.1 is an expression of the "conservation of momentum law" as it is called. "Momentum" is defined as the product of mass and velocity. The general law is expressed as the sum of the forces on an object is equal to the rate of change of its momentum. Equation A.1 also provides a way todefine mass as that quantity in which the force on an object enables its acceleration, accordingly.

Equation A.1 is given in symbols. These symbols are like acronyms of science. The symbols are used as simplified and shortened nicknames. Often the nicknames have been chosen in an obvious way: F for force, a as acceleration, and m for mass. Many scientific texts will use the same symbols for the same quantity. But soon one runs out of the alphabet, as single letters are generally used, and other alphabets, mainly Greek, are employed. The beginning student in science needs to be aware of such Greek terminology to converse smoothly with equations of science. Table A.1 lists the upper and lower case letters of the Greek alphabet and their English names. For comfort when dealing with scientific expressions it pays to know some Greek.

Let us investigate Newton's law and consider the meaning of the terms. Acceleration is the rate of change of velocity. For example, if the car speeds up from 0 to 60 mph in 6 seconds, its acceleration is 60 mph/6 seconds or 10 miles per hour per second. It is proper to express this in consistent units, not hours and seconds together. Also if seconds are to be used, generally the foot is a better choice of length over mile. Now we have an exercise in converting from one set of units for length, miles and feet, and one set of units for time, hours and seconds. This can be done in a number of ways. We need to look up how units of one measure are converted to alternative units in that measure. Hours can be changed to seconds (3600 s = 1 h) and miles can be changed to feet (1 mi = 5280 ft),

TABLE A.1

Greek Alphabet Names, Uppercase/Lowercase

Α/α	Alpha	Ν/ν	Nu
Β/β	Beta	Ξ/ξ	Xi
Γ/γ	Gamma	Ο/ο	Omicron
Δ/δ	Delta	Π/π	Pi
Ε/ε	Epsilon	Ρ/ρ	Rho
Ζ/ζ	Zeta	Σ/σ	Sigma
Η/η	Eta	Τ/τ	Tau
Θ/θ	Theta	Υ/υ	Upsilon
Ι/τ	Iota	Φ/φ	Phi
Κ/κ	Kappa	Χ/χ	Chi
Λ/λ	Lambda	Ψ/ψ	Psi
Μ/μ	Mu	Ω/ω	Omega

or we might use 1 ft/s is 0.682 mph. Let us use these conversion factors to change from 10 miles per hour per second to ft/s/s or ft/s^2:

$$\frac{60 \text{ mph} \times \dfrac{1 \text{ ft/s}}{0.682 \text{ mph}}}{6 \text{ s}} = 14.67 \frac{\text{ft/s}}{\text{s}} \text{ or } \frac{\text{ft}}{\text{s}^2}$$

Note how (mph) as a unit measure cancels in the numerator and denominator, and we are left with ft/s^2—the units of acceleration.

Instead of numbers we could express acceleration in terms of the ratio of velocity to time, or more precisely

$$\text{Acceleration} = \frac{\text{Change of velocity}}{\text{Change of time}}$$

Symbolically, we could represent a for acceleration, v for velocity, and t for time. Further, we could use the symbol capital delta, Δ, in the Greek alphabet, synonymous with D in the English alphabet, to mean the operation: *change of*. Then the previous equation in words can be expressed completely in symbols as

$$a = \frac{\Delta v}{\Delta t} \tag{A.2}$$

More precisely, Newton realized that the interval in time needed in the formula should be very small if he was to compute the precise acceleration of an object as it moves. As a consequence, he invented the *calculus* in which Equation A.2 becomes the *time derivative of* v as Δt becomes very small. The acceleration can be expressed as the instantaneous rate of change of velocity over time. This book will stop short of the calculus, but one should appreciate that there are higher forms of mathematics that enable more complex and precise computations.

A.3.4 Laws of Nature

In general, the three conservation laws can be expressed in terms of rate equations. These rates are *time derivatives*. For example, the rate of energy (E) is expressed as $\Delta E/\Delta t$ as Δt gets small is written as dE/dt for its *time derivative*.

The three laws of nature, conservation of mass, energy, and momentum, can be expressed for an isolated system as follows:

1. $\frac{dm}{dt} = 0$, since the mass does not change over time.
2. $\frac{dE}{dt} = 0$, since energy does not change over time.
3. $F = m\frac{dv}{dt}$, as now acceleration is expressed as the rate of change of velocity.

These laws, using the calculus, allow scientists to mathematically express the laws of nature. They apply to all processes and must always be satisfied. Consequently, if we wish to explain or predict an aspect of any process, we must apply these equations to that process and render a solution. In this way mathematics is the tool of the scientist to describe aspects of nature in terms of concrete numbers, each with appropriate units for a specific quantity. For most applications, this set of three equations cannot be solved exactly to produce a simple formula. Thus, the laws of nature can be expressed in mathematical terms and in conceptual and measurable quantities but do not easily render specific solutions. Indeed, the process of expressing these laws in complete mathematical terms has evolved over time as more phenomena could be represented. Computer models solve equations representing these laws in terms of the derivatives. It is not a trivial process.

Scientists began with simple studies to represent a law in mathematical terms. For example, Newton (~1700) used solid objects to first elucidate the conservation of momentum principle. About 60 years later, Daniel Bernoulli extended it to flowing water, but he ignored the frictional effects of water flowing through a duct. About another 60 years later Navier and Stokes included this friction. Their description became much more complicated, but the law of nature was the same. The expression of Newton's law for a flowing fluid, such as water or air, must consider all of the forces present and must represent the rate of momentum at every point in the flow and at every time. The Navier–Stokes equation does this in very complex mathematical terms. In general, the basic three laws of nature that govern all motion, mass, and energy have been expressed in deeper and more complex mathematics over the last 300 years.

Don't get nervous. You will not be asked to solve them. In fact, the biggest computers today can only solve them in very limited ways. We do not yet have the magic universal calculator. Computers solve them approximately. The approximations are not just in the numbers, but also in how to express the unsteady phenomena of fluid turbulence, the rate of the combustion reaction, and the complexities of heat transfer. In addition, the properties of materials are not always precisely known.

A.4 Solution by Algebraic Formula

The alternative to precise mathematical solutions is to make observations and measurements, use the laws of nature to the extent possible, and develop formulas for specific, rather than general, problems. These formulas are the results of a solution for limited aspects of a specific process. They have been developed using implications of the conservation laws and careful experimental data so that an algebraic equation gives a result that holds over a wide range of conditions. These are the formulas you will meet in this text.

An algebraic equation will likely have some unusual algebraic operations, at least to the user that has forgotten or never learned algebra. We will review the principles of elementary algebra here.

A.4.1 Algebraic Operations and Formulas

The formulas you will encounter in this text will be in terms of elementary algebra. This algebra involves operations with numbers and symbols consisting of normal arithmetic, special functions, powers, and roots. We have implicitly been using algebra to describe the laws of nature so far. But let us backup and become more elementary.

As an example, consider the problem of estimating the time to drive from Washington, DC to New York City by car averaging 50 mph. The distance is about 230 miles. We can formulate the problem into an equation. Let us choose

v as the velocity of the care
x as the distance
t as the time

Then,

$$t = \frac{x}{v}$$

or computing

$$t = \frac{230\,\text{miles}}{50\,\text{miles/hour}} = 4.6\,\text{hour}$$

Notice we have the units

$$\frac{\text{miles}}{(\text{miles/hour})}$$

If we multiply this complex fraction in terms of units by hour/hour (anything divided by itself is unity or one), we get

$$\frac{\frac{\cancel{\text{miles}}}{\cancel{\text{miles}}}}{\cancel{\text{hour}}} \cdot \frac{\text{hour}}{\cancel{\text{hour}}} = \frac{1}{1} \cdot \text{hour} = \text{hour (h)}$$

Thus, the answer comes out in the units of hour.

A.4.1.1 Power Operations

Let us consider another example. What is the area of a track of land 10 meters (m) × 10 m? Let x be the length of one side of the square track and A stands for area. Our formula is

$$A = x \times x = 100 \text{ m}^2$$

The symbol × means *multiply*, but here we are multiplying x by itself. Algebra introduces a shorthand for this operation with $x \times x$ as x^2 which means x *squared* or to the power 2. Here, the power 2 means multiply x by itself.

Let us carry this further. Extending this example to the calculation of volume (V) of a cube have each side of length x

$$V = x^3$$

is the formula. Now we have x^3, or this is called "x-cubed" or x to the power 3, meaning it is multiplied by itself three times. In general, we might write x^n. But what if n is not an integer? That could prove troublesome. Let us investigate this issue.

A.4.1.2 Roots and Fractional Powers

What if we know that the volume of the cube is 1000 cubic meter (m^3)? How can we find the length of a side? We need to find the *cube root* of V. This is the inverse of the cube operation or power-3 operation. What number, when multiplied by itself three times, will give 1000? Of course, we easily see that number as 10, but the cube root of 965 is not something you can do in your head. We could do it by trial and error, and estimate the answer. However, today we are blessed with electronic calculators that can perform all algebraic operations at the stroke of a button. Let us proceed with the language and symbolism of algebra. The operation of taking a cube root is denoted as follows:

$$\sqrt[3]{V} = \sqrt[3]{x^3} = x$$

The cube root has annihilated the cube operation on the x, and we return to x alone.

Alternative, we can write this root operation as a fractional power $\sqrt[3]{V} = V^{1/3}$. The 1/3 power is equivalent to the root operation.

Note: $x^3 = x \times x \times x$, so raising it to the 1/3 means undoing the cube operation,

$$(x^3)^{1/3} = x^1 \quad \text{or} \quad V^{1/3} = x$$

Thus, we have preformed algebraic manipulation of the formula, by reversing the process of finding V from x, to finding x from V.

A.4.1.3 Scientific Calculators

The operation of having a fractional power implies a root operation. But what if the power is something like 5/2 or 2.5? Consider the number 4 to the power of 2.5. We can dissect its operation as follows:

$$4^{2.5} = 4 \times 4 \times 4^{0.5} = 16 \times 2 = 32$$

Perhaps that was relatively easy, as we could readily recognize the square root of 4 as 2. If the power was 2.4 instead the answer is lower, and can be found as 27.8576…. Our only recourse for obtaining this number is to use an electronic calculator. These devices can now be purchased at low prices and can even be downloaded free from the web. They are referred to as "scientific calculators." Figure A.1 is an example of such a calculator. It allows for many algebraic operations.

The process of computing $4^{2.4}$ is done by using the y^x-key. In this case 4 is typed for y and 2.4 is inputted for x. Pressing the equal button gives the answer. In this class you will need to perform operations like this, but in sequence, such as $4^{2.4}/10.2$. So getting familiar with a calculator is a must. While the precise answer to $4^{2.4}/10.2$ is 2.731…, it could well have been approximated by using $4^{2.5}/10$ giving 32/10 or 3.2. We know it should be lower, and this approximation shows we are on the right track in using the electronic calculator. It is always prudent to do such approximations when performing a series of operations on the calculator. The student should be aware that scientific calculators differ in their mechanics, so there is learning process for each.

A.4.1.4 Negative and Power Zero

Before leaving power operations we should consider what happens if a power is zero or negative. It should be obvious that $x/x = 1$. Writing this as

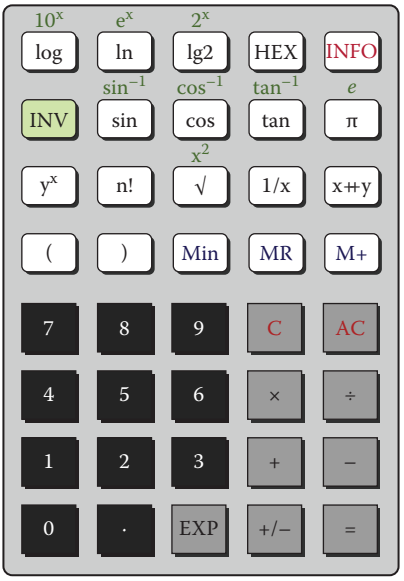

FIGURE A.1
Typical scientific calculator.

powers, we consider the term in the denominator as a negative power. So the equivalent of $x/x = 1$ can be written as

$$x^1 \times x^{-1} = x^{1-1} = x^0 = 1$$

Thus, we see that the zero power for any quantity gives 1, and multiplying like terms with powers can be simplified by adding the powers. For example,

$$\frac{x^{3/2}\sqrt{xy}}{y^{2/5}} = \frac{x^{3/2}x^{1/2}y^{1/2}}{y^{2/5}} = x^{3/2+1/2}y^{1/2-2/5} = x^2y^{1/10}$$

The beginning student of algebra should master these power operations to be better versed at manipulating fire formulas.

A.4.1.5 Constants in Science

In nature, some *constants* often show up and they are given a special symbol. For example, the area of a circle of radius, r, is

$$A = \pi r^2$$

where π (pi, the Greek letter) is one such constant.

Rounded off to five places,

$$\pi = 3.14159.$$

In Figure A.1, it is seen that the calculator has an individual button for the exact value of π.

Another constant is the quantity called e given to five places as

$$e = 2.71828.$$

For the calculator shown in Figure A.1, e shares the same button for π and can be accessed by pressing a shift key. These are special numbers you are likely to see in the formulas found in fire science.

While π shows up in formulas related to circular effects, it is not obvious why the e shows up. In science, there are many natural processes that, by the conservation laws and the calculus, can be shown to occur with e to some power involving length or time. The expression e^x is called the "exponential function of x," meaning the number e is taken to the x-power. This function occurs in a process where a quantity depends on its own rate of change. For example, if the power produced in a fire depends on the rate of change of that power, then with P standing for the firepower, it will behave as

$$P = P_i e^{Ct} \tag{A.3}$$

where

P_i is the initial value of P
t is time
C is a constant

If C is negative, the power decreases in time. Of course this happens for fires that die out. On the other hand, if C is positive, the power will continue to increase indefinitely over time. Mathematically, this can only reach a very large number at the end of time called "infinity." Here, a mathematical solution gives an answer that is not physically meaningful. With C positive, the fire will grow, but the formula does not take into account the availability of air that will eventually limit this fire growth. We say P grows (or decays) *exponentially* in time.

A.4.1.6 Logarithms

Consider the exponential decay process. We may wish to compute the time it will take for the power to decay to one-half of its original value. This is commonly called the "half-life." We need an operation that can reverse the

power process on the number *e*. This inverse operation is called the "natural logarithm" given by the symbol ln. The process is described as follows:

$$\ln\left[e^{Ct}\right] = Ct \tag{A.4}$$

Logarithms of numbers have been computed and can be found in mathematical tables, but today we can easily access them on the scientific calculator. In Figure A.1 it is seen that there is a button for ln, meaning taking the logarithm of x as $\ln(x)$. Also notice on the same button is the inverse operation of e^x. With this ability, we can compute the half-life:

$$\ln\left(\frac{P}{P_i}\right) = \ln\left(\frac{1}{2}\right) = \ln(e^{Ct}) = Ct$$

It can be determined from a table or the calculator that $\ln(1/2) = -0.693\ldots$ roughly. Consequently, the half-life is about $-1.44/C$. For this to give a positive number for time, the C must be negative for decay and must have units of reciprocal time, for example, 1/seconds or s^{-1}. For example, if $C = -0.01\ s^{-1}$, then the half-life time is 144 seconds.

This ln operation implies taking the logarithm to the base *e*. There is another logarithm taken to the base 10 and its operation is denoted by log. Its inverse operation is $\log(10^x) = x$. It too is listed on the calculator. These special numbers *e* and π, along with the logarithmic operations are likely to show up in scientific formulas, and therefore a scientific calculator is essential.

A.5 Graphs

Graphs are often employed as an alternative to interpreting formulas through algebra. In fact, many formulas for fire calculations have resulted from plots of data, and then a formula was developed directly from the graphical fit to these data. So reading a graph is also one way of addressing an equation. For example, a plot of $P = P_i e^{Ct}$, where P_i is taken at 100 kW and C is taken as $(-0.01\ s^{-1})$, is given in Figure A.2.

In Figure A.2 a linear scale is used on each of the axes in which the increments on the axes are all equal. On the horizontal axis, the smallest increment is 20 seconds (s). On the vertical axes, the smallest increment is 5 kW. The graph also shows the half-life solution when the power has decreased to 50 kW. But as the graph approaches zero below a power of about 5 kW, it is difficult to read with any precision.

An alternative graphical presentation that allows more accuracy in reading these low power results is to employ a graph with a logarithmic scale

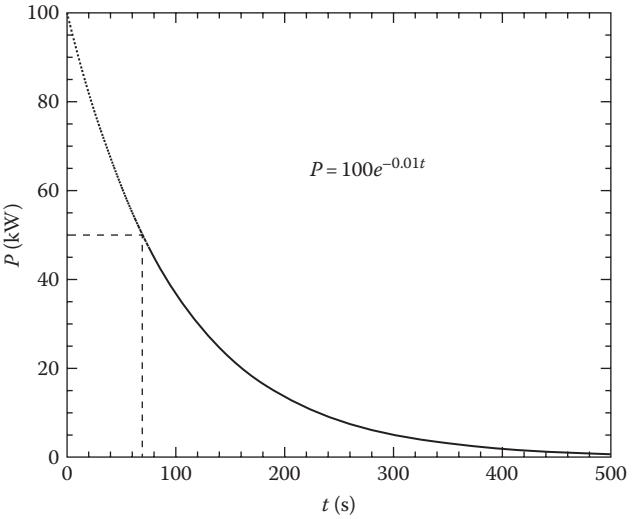

FIGURE A.2
Linear-scale plot.

on both axes. This graph is shown in Figure A.3, and it greatly expands the low-scale precision. In a logarithmic scale the major increments are broken into decades, and within each decade there are increments inclusive of 1–10. These increments within a decade are not equal in length. Therefore, extrapolation of results must be done with care.

A.6 Units and Conversions

A formula and a graph will contain various symbols for specific quantities and they will have units. These units must be consistently used or the results will be wrong. If the answer on the left-hand side is to be in meters, the formula must be algebraically computed from the terms on the right-hand side to also yield meters. A simple example can illustrate this. Suppose you know the area of a room floor and the length of one of the sides, and you wish to find the length of the other side. You are given that the area is 18.3 m^2 and a side is given as 12.5 ft. These units are inconsistent. Our formula for computing the side, call it s_2, with the given side as s_1, from the area, A is

$$s_2 = \frac{A}{s_1}$$

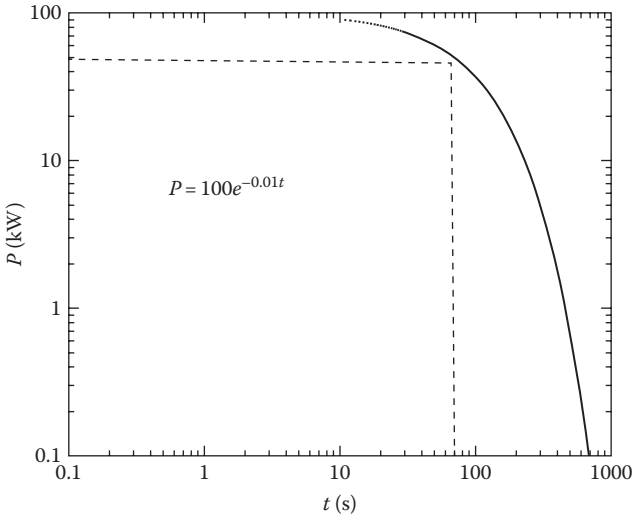

FIGURE A.3
Logarithmic-scale plot.

Let us maintain meter units, as you will find this more common in science. We need to convert ft to m. Conversion tables are available to making these changes and must be utilized. Table A.2 is a listing of conversion factors that you might find most pertinent to the subject of this course. It emphasizes the conversion of units to the Standard International (SI) system. That system is most often used in science and the formulas of fire are mostly represented relative to SI units. The SI unit for length is m. The other key units are mass in kilograms (kg) and time in seconds (s). All of these units have shorthand symbols for them as indicated. From Table A.2, 1 ft = 0.305 m as equivalent lengths. This equivalence can be used to formulate an algebra for converting, that is,

$$12.5\ \text{ft} \times \frac{0.305\ \text{m}}{1\ \text{ft}} = 3.81\ \text{m}$$

In this process, the conversion factor 0.305 was rounded off to three places and the answer has been rounded off to three as well. This too is consistency. Now the problem can be completed in consistent units of m. Substituting into the equation gives

$$s_2 = \frac{A}{s_1} = \frac{18.3\ \text{m}^2}{12.5\ \text{ft} \times \dfrac{0.305\ \text{m}}{1\ \text{ft}}} = 4.80\ \text{m}$$

TABLE A.2

Approximate Conversions from English to SI Units

Length				
in.	Inch	25.4	Millimeters	mm
ft	Feet	0.305	Meters	m
yd	Yards	0.914	Meters	m
mi	Miles	1.61	Kilometers	km
Area				
$in.^2$	Square inches	645.2	Square millimeters	mm^2
ft^2	Square feet	0.093	Square meters	m^2
yd^2	Square yard	0.836	Square meters	m^2
Volume				
ft^3	Cubic feet	0.028	Cubic meters	m^3
yd^3	Cubic yards	0.765	Cubic meters	m^3
Mass				
oz	Ounces	28.35	Grams	g
lb	Pounds	0.454	Kilograms	kg
Force and pressure				
N	Newton	$kg\text{-}m/s^2$		Alias
Pa	Pascal	N/m^2		Alias
lbf	Pound-force	4.45 newtons		N
lbf/in^2	Pound-force per sq. inch	6.89 kilopascals		kPa
Energy				
J	Joule	N-m		Alias
Btu	British thermal units	1.055 kilojoules		kJ
cal	Calorie	4.187 joules		J
Power				
W	Watt	J/s		Alias
hp	Horsepower	0.746 kilowatt		kW
Temperature				
°F	Fahrenheit	(°F – 32)(5/9) Celsius		°C
K	Kelvin	°C + 273.15		Alias

Notice in the algebra of dealing with units that ft cancel, and the m^2 cancels with m to give the length in units of m.

A.6.1 SI Units: Aliases or Derived Units

The conservation laws provide a basis for giving the equivalence of units and minimizing the number of independent units actually needed. However,

as in all practices, names spring up to simplify certain collection of units into *aliases*. In the SI system we need only deal with kg, m, and s as the primary units. Here we have covered mass, length, and time. But what units should we give to *force*, a distinct quantity? From Newton's law or the conservation of momentum, we know force is always equal to mass times acceleration. This means that in terms of the primary SI units we might give force the units of kg times m/s^2. However, this name, kg-m/s^2, is cumbersome, so it is given an alias name of Newton (N), as 1 N = 1 kg-m/s^2. This is a so-called derived unit.

How about *energy*? Well, energy is measured by work, and work is the product of force and length. Therefore, we can now call energy units in the SI system as N-m. This already has the alias N in it, yet we wish to be simpler, and the alias *joule* (J) is introduced: 1 J = 1 N-m, another derived unit. Finally, power is the rate of energy and is a commodity that is purchased in kilowatts—another alias, the *watt* (W). 1 W = 1 J/s. In this way many terms in science can be represented in terms of the basic units of mass, length, and time: kg, m, and s. These, and other aliases, with their conversions to SI units are listed in Table A.2.

A.6.2 Equations and Dimensions

Let us consider one final example to show how consistency can be maintained in an equation. We take an example of a frequently used formula for the ratio of flame length (L) to diameter (D) for a pool fire given as

$$\frac{L}{D} = 3.87Q^{*2/5} - 1.02 \tag{A.5}$$

As L/D is the ratio of two length dimensions, flame length to diameter, they must both be in the same units. Also these same units will cancel, leaving no units for L/D. The quantity L/D is called a *dimensionless* quantity or variable. Of course the L and D each have units, and as they must be consistent, they can both be in ft or both in m.

In Equation A.5, the left-hand side is dimensionless, and that means the right-hand side must also be dimensionless. The numbers here have no units, and the variable Q^* (Q-star, some have given it the name, the Zukoski number) must also be dimensionless. However, Q^* is a quantity composed of many factors, each having units. Often scientists compose equations that are dimensionless with the intent that they are valid over a wide range of conditions. Also the dimensionless nature of the equation makes it more compact and reduces the number of variables. Here Q^* is

composed of the several properties and the variable for the firepower, $\dot{Q}$ in this fashion:

$$Q^* = \frac{\dot{Q}}{\rho c_p T \sqrt{g} D^{5/2}} \tag{A.6}$$

where here we have the properties of air given as

Density, $\rho = 1.20$ kg/m^3
Specific heat, $c_p = 1.00$ kJ/kg-K
Temperature, $T = 293$ K

The SI unit for temperature is in kelvin (K) and can be considered as an alias for Celsius (°C). In fact, K is a temperature scale that has its zero point associated with no more energy in the material. Celsius is basically a scale of reference for temperature that uses the freezing and boiling points of water as 0 and 100, respectively. When the quantity of temperature stands alone in an equation, the absolute temperature scale of K must be used over °C. If it appears as a temperature difference, either scale can be used.

One more term is contained in the denominator of Equation A.6. It is g, standing for the gravitational force on a unit mass. For the Earth, this is about 9.81 N/kg. Note, as a newton is an alias, this can be also equivalently written as 9.81 m/s^2. This now has units of acceleration, and g is also called the acceleration due to gravity.

Let us compute these terms in the denominator of Equation A.6 with the air properties specified. We note that the units combine as follows when treated with algebraic operation:

$$1.20\frac{\text{kg}}{\text{m}^3}\times 1.00\frac{\text{kJ}}{\text{kg-K}}\times 293\text{ K}\times\left(9.81\frac{\text{m}}{\text{s}^2}\right)^{1/2} = 1101.2\frac{\text{kJ}}{\text{s-m}^{5/2}}\text{ or }\frac{\text{kW}}{\text{m}^{5/2}}$$

Here we have recognized the alias: kW for kJ/s. Now if we express the firepower in kW and the diameter in m, Q^* will remain dimensionless and consistent with L/D.

Often the same equation as (A.5) will be given in specific units. This follows from substituting the air property and gravity term as 1101.2 kW/m$^{5/2}$ into Equation A.5 to obtain

$$\frac{L\,(\text{m})}{D\,(\text{m})} = \left[0.235\text{ m/kW}^{2/5}\right]\left[\frac{\dot{Q}\,(\text{kW})}{[D\,(\text{m})]^{5/2}}\right]^{2/5} - 1.02$$

or

$$L\,(\text{m}) = \left[0.235\text{ kW}^{-2/5}\right]\left[\dot{Q}\,(\text{kW})\right]^{2/5} - 1.02D\,(\text{m}) \tag{A.7}$$

Equation A.7 is the dimensional form of Equation A.5 in the units of m and kW. Here the units are all indicated, and even the number 0.235 has units, in contrast to the numbers in the dimensionless equation (A.5).

When an equation is given as a formula, the units are very important. If it is dimensionless to begin with, consistent units must be used for each term. If it is dimensional, specific units must be used for the variables in the equation and nothing other. In Equation A.7, the units of kW must be used for the firepower and the units of m for diameter; then the flame length is computed in m also. I was told of the use of Equation A.7 in a court case where two experts got very different answers. The opposing expert used ft for diameter and got a negative flame length. It may have scored points in that expert's testimony initially, but a lot of credibility was lost on rebuttal. Units are very important. They must be used consistently, or the results of the equation will be wrong. Take care.

A.7 Summary

Mathematics is required to solve the laws of science. The key laws of science embrace

1. Conservation of mass
2. Conservation of energy
3. Conservation of momentum

These laws must hold for every natural process and can be expressed in mathematical terms. Yet, even modern computers are not capable of solving all aspects and can only give approximate answers. Alternatively, science has found specific solutions in terms of single algebraic equations. The solution of these equations into precise numbers requires an understanding of algebra and the appropriate manipulation of units. SI units are mostly used in science, and conversion to these units is essential in applications. The basic SI units, for purposes of fire science, involve mass in kg, length in m, time in s, and K for temperature. Combinations of these units are sufficient for describing all scientific variables and properties of fire. However, it is practice to give shorthand alias names to the various combinations. This occurs for force (N), energy (J), and power (W). In the computation of any algebraic equation, it is essential that the units are consistent so that the units on the right and the left side of the equation reduce to the same quantity. A brief review of algebra was presented with emphasis on the use of powers and roots. Exponential and logarithmic functions were discussed. A scientific calculator is essential for performing these operations. Alternatively, it

was shown how graphical displays of the solution of an equation could be presented in linear and logarithmic scales.

Review Questions

1. What equation shows the equivalence of mass and energy?
2. What equation relates force and mass?
3. How can energy be recognized?
4. What are the basic SI units?
5. Can energy or mass of the universe ever be destroyed?
6. Simplify $\dfrac{x^{5/2}y^{1/2}e^{2x}}{y^{2.3}\sqrt{x}}$.
7. Compute $\pi e^{0.6}$.
8. Compute the height of a flame in inches from Equation A.7 for firepower of 18,450 W and a diameter of 60 cm.
9. What force, in N, is required to hold 100 kg in Earth's gravitational acceleration field of 9.81 m/s^2?
10. Name several derived units in the SI system.

True or False

1. In the chemical reaction of fire, mass is destroyed.
2. Atoms are a form of mass.
3. Heat produced in a fire is due to a rearrangement of the atoms into new molecules.
4. SI units can include feet for length.
5. Newton's law is the conservation of momentum.
6. Units in an algebraic scientific formula must be consistent.
7. Energy is basically just heat alone.
8. The boiling point of water at normal atmospheric pressure is 80°C.
9. The units for acceleration are ft/s.
10. Logarithmic scales on graphs are arranged in decades.

Activities

1. Buy or download an inexpensive scientific calculator and learn how to perform simple algebraic operations.
2. Explore tables and conversion techniques found in books or on the internet.
3. Explore the conservation laws and their history.
4. Review algebra.
5. Practice manipulating units in scientific equations.

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Glossary

Absorption coefficient: That property that pertains to the amount of radiation absorbed per unit length.

Activation energy: Energy per mole of fuel needed to initiate ignition.

Adiabatic flame temperature: The maximum possible temperature in the chemical reacting zone with no heat lost.

Arc mapping: A method of locating beads due to electric wire circuit faults due to fire in order to try to determine the location of the early fire.

ASTM E 84: A standard providing a test (Steiner tunnel test) developed by Underwriters Laboratories to examine wind-aided flame spread under ceiling mounted materials.

ASTM E-162: A standard providing a radiant fuel test to measure the flammability of materials under downward spread.

ASTM E-648: A standard providing a flame test for floor-covering materials.

ASTM E-1321: A standard providing a test to determine data for ignition and flame spread.

Autoignition: Initiation of fire by chemical process inherent in the material without a pilot; specific fuel concentration and temperature are usually needed.

Autoignition temperature: The lowest temperature at which a mixture of fuel and oxidizer can propagate a flame without the aid of an initiating energy source (pilot).

Backdraft: The sudden eruption of fire in a compartment due to the accumulation of fuel gases and the introduction of fresh air; results in a pressure increase.

Black body: A material emitting the maximum possible radiant energy.

Blow-off: Extinguishment of a flame due to wind or high-speed flow.

Boiling point: The maximum temperature at which a liquid can evaporate under normal atmospheric conditions; equilibrium temperature for a liquid and its vapor to coexist at 1 atmosphere of pressure.

Boundary layer: Fluid region near a surface in which viscous or heat transfer effects dominate.

Buoyancy: An effective force on fluid due to density or temperature differences in a gravitational field.

Burning rate: The mass of fuel consumed in the fire per unit time.

Burnout: Point at which flames cease.

Carboxyhemoglobin: Carbon monoxide hemoglobin compound found in the blood due to inhalation of carbon monoxide.

Chain branching: Propagating sequence of chemical reactions steps that produce more unstable species than it consumes; terminates in ignition.

Characteristic combustion length: A length scale representative of the fire size; proportional to the power 2/5 of the firepower.

Charring: The production of a solid carbonaceous residue on heating or burning a solid.

Chemical equation: An equation showing the proportions (by mass or moles) of the fuel, oxygen, and products in a chemical reaction in which the atoms are conserved.

Chemical kinetics: Refers to the study of chemical reaction rates.

Chemical reaction: Chemical interactions between molecules to form new molecules while conserving atoms.

Clean-burn: A less sooty region on a noncombustible wall after a fully developed room fire; appears lighter in shade compared to surrounded wall.

Combustion: A chemical reaction, involving oxygen, that produces a perceptible amount of energy—fire or controlled fire.

Completeness: Pertaining to a combustion process going to its most stable state, an ideal reaction; water and carbon dioxide would be the complete products of combustion for hydrocarbon fires.

Concentration: The percentage of material per unit mass (or volume) of its mixture.

Conduction: Heat transfer due to molecular energy transfer following Fourier's Law.

Configuration factor: Fraction of radiation received by a target compared to the total emitted by the source—view factor.

Conflagration or mass fire: A fire over a large tract of land; the flames are much shorter than the horizontal extent of the fire.

Convection: Conduction heat transfer from a moving fluid (gas or liquid) to a solid surface.

Convective heat transfer coefficient: A quantity that represents the ability of heat to be transformed from a moving fluid to a solid surface expressed in terms of heat flux per unit temperature difference.

Cracking: Pyrolysis; breaking gaseous molecules into other molecules, usually by heat.

Critical heat flux: A threshold level of heating below which ignition (or in another context, flame spread) is not possible.

Crown fire: Fire spreading in the tops of trees in a forest fire.

Deflagration: A propagating premixed flame at speeds below the speed of sound.

Detonation: A high-speed premixed flame preceded by a shock wave.

Developing fire: The early stage of growth (in a compartment fire) before flashover and full involvement; almost like burning in the open.

Diffusion: Process of species transport in a mixture from its high to low concentration.

Diffusion flame: A flame in which the fuel and oxygen are transported (diffused) from opposite sides of the reaction zone (flame).

Dimensionless: Having no units of measure (terms combine to produce no units).

Dose: The accumulation of product concentration inhaled over time; the integral of concentration over time.

Eddies: Rotating regions of a fluid.

Emissivity: That property (having values 0–1) that gives the fraction of being a perfect radiation emitter due to temperature.

Energy: A state of matter representative of its ability to do work or transfer heat.

Energy release rate: The energy produced by the fire per unit time; fire power; HRR.

Entrainment: The process of air or gases being drawn into a fire, plume, or jet.

Equation of state: An equation to relate thermodynamic properties—commonly pressure, temperature, and density for a gas.

Equivalence ratio: The ratio of available fuel to air times the stoichiometric air-to-fuel ratio or $(\text{fuel/air})_{\text{available}}$ divided by $(\text{fuel/air})_{\text{stoichiometric}}$.

Equivalency: The statement in regulations allowing for alternatives by design.

Evaporation: The process of gas molecules escaping from the surface of a liquid.

Field model: A type of computer fire model that attempts to predict conditions at every point; also known as a computational fluid dynamics model.

Fire: An uncontrolled chemical reaction producing light and sufficient energy.

Fireball: An increasing, short-lived, rising ball-shaped flame due a sudden release and ignition of fuel gases.

Fire plume: The flame and gases emanating from a burning object.

Fire point: The minimum surface temperature needed by the liquid to sustain a diffusion flame.

Firepower: Chemical release rate of energy in a fire.

Fire spread: The process of an advancing fire front: smoldering or flaming.

Firestorm: Large conflagration that creates large winds and other weather effects.

Fire tetrahedron: A three-dimensional representation of the fire triangle with chain branching.

Fire triangle: A concept describing fire as consisting of three ingredients: fuel, oxygen, and energy.

Fire whirl: A flaming tornado.

Flame height: The vertical measure of the combustion region, usually luminous.

Flame spread: The process of advancing the fire front in air, along surfaces, or through porous solids.

Flammable: Indicates that burning can occur; originates from *inflammable*.

Flashover: A dramatic event in a room fire that is due to energy production exceeding energy losses; manifested by a sharp rate of increase

in temperature of the smoke; ends with a fully developed fire that involves all the contents in flames if sufficient air or terminates with a ventilation-limited fire without sufficient air to burn all of the gaseous fuel produced in the room.

Flashpoint: The temperature of a liquid fuel, theoretically corresponding to the lower flammable limit of its evaporated vapor and the point of piloted ignition.

Fluid mechanics: The study of fluid motion.

Flux: Pertains to mass or heat flow rates per unit area.

Forced flow: Refers to air flow produced by wind or a fan.

Free burning: Burning in open air.

Frequency: Cycles per unit time (measured in hertz, cycles per second).

Fuel lean: Description of fuel burning in an excess supply of air.

Fuel limited: State of a compartment fire where the air supply is sufficient to maintain combustion.

Fully developed: State of a room fire at which the maximum possible energy release is attained; either all the fuel burns or all of the incoming air is consumed.

Heat: Energy transfer due to temperature difference.

Heat flux: Heat flow rate per unit area of flow path.

Heat of combustion: The energy released by the fire per unit mass of fuel burned.

Heat of gasification: Energy required to produce a unit mass of fuel vapor from a solid or liquid.

Heat release parameter, HRP: Ratio of heat of combustion to heat of gasification.

Heat release rate: Same as firepower.

Heat transfer: The transport of energy from a high-to-low temperature.

Hemoglobin: Compound in blood that transports oxygen or carbon monoxide.

Hifukusho-ato district of Tokyo: Area where many died in a fire whirl in 1923.

Hot surface ignition: Ignition of a flammable mixture due to a hot surface; usually higher than the AIT.

Humidity: The property of the water–air mixture that measures the amount of water present relative to the equilibrium concentration.

Hyperthermia: Heat stress.

Ignition temperature: The surface temperature needed to cause ignition in solids.

Incomplete combustion: A combustion process that does not go to the most stable species such as H_2O and CO_2.

International System of Units or Standard International (SI) Units: The system of units for measurement generally adopted by the science community.

Irritant gases: Acid gases and other hydrocarbon by-products that can cause pain on contact or with inhalation.

Jet flame: Flame due to a high-velocity fuel supply; exceeds buoyancy effects.
Kelvin (K): Absolute Celsius temperature scale, ~273 + °C.
Laminar: Refers to orderly, unfluctuating fluid motion.
Line fires: Elongated relatively thin region fires on a horizontal fuel surface; indicative of wildland fires.
Mass burning flux: Burning rate per unit area.
Mass concentration: Ratio of species mass to mixture mass; also referred to as mass fraction.
Mass loss rate: The mass of fuel per unit time vaporized under fire heating but not necessarily burned.
Mass optical density: Optical property related to the yield of particulates in smoke.
Narcosis: Effect of inducing sleep.
Natural flow: Refers to air flow induced by buoyancy.
Neutral plane: The height above which smoke can flow out of a compartment or building wall; the height of zero pressure difference across a partition.
Newtons Second Law of Motion: Relates force on a body to its mass and resulting acceleration.
Opposed flow: Refers to air flow in the direction opposite to the fire spread.
Overventilated: More than stoichiometric air is available.
Oxygen bomb: A device for measuring the maximum energy released in combustion for a fuel.
Oxygen consumption calorimeter: Device to measure energy release rate in fire by utilizing the approximate constancy of the heat of combustion per unit mass of oxygen, ~13.1 kJ/g.
Oxyhemoglobin: Oxygen-bearing hemoglobin in blood.
Parts per million, ppm: Concentration based on 10^6 parts of the mixture.
Pattern analysis: The process of attempting to interpret patterns in the debris of a fire.
Performance codes: Regulations providing for engineering analysis.
Performance-based design: Design process to meet specific engineering objectives.
Piloted ignition: Ignition of a flammable fuel–air mixture by a hot spot, electric arc, or small flame (pilot).
Pool fire: Fire involving a horizontal fuel surface, usually symmetrical.
Premixed flame: A flame in which fuel and air are mixed first before combustion.
Prescribed burning: Intentional burning of forest terrain to improve conditions.
Products: Chemical compounds produced by fire.
Pyrolysis: The process of heating fuel to cause decomposition to a gas.
Radiation: Heat transfer due to electromagnetic energy transfer, such as light.
Radicals: Short-lived unstable molecules, such as OH.
Rankine (°R): Absolute Fahrenheit temperature scale, ~460 + °F.

Reradiation: The radiation reemitted from a heated surface.
Respiration minute volume, RMV: Inhalation rate.
Shock wave: Abrupt change in temperature and pressure due to a flow instability caused by speeds in excess of the speed of sound.
Smoke: Gases, no longer chemically reacting, that emanate from the fire.
Smoke visibility: Distance over which a human can perceive objects through smoke.
Smoldering: A slow combustion process between oxygen and a solid fuel.
Soot: Carbonaceous particles produced in flames.
Species: Another name for chemical compounds, usually gases.
Specific heat: Property that measures the ability of matter to store energy.
Spontaneous combustion: A process by which combustion occurs after a very low heating self-incubation period between a fuel and oxidizer, or decomposing fuel; leads to smoldering or flaming.
Stack effect: Motion of air and smoke due to buoyancy, usually in a tall building.
Stoichiometric: Refers to the amount of air needed to burn the fuel (and to combustion products formed).
Stoichiometric air-to-fuel mass ratio: The ratio of air to fuel by mass needed to burn all the fuel to completion.
Surface tension: A force within the surface of a liquid.
Synthesis: Recombination of molecules.
Thermal conductivity: The property of matter that represents the ability to transfer heat by conduction.
Thermal energy: Energy directly related to the temperature of an object; internal energy.
Thermal inertia: A thermal property responsible for the rate of temperature rise, $k\rho c$.
Thermally thin: Refers to a material that has a nearly uniform temperature during heating.
Thermal response parameter: A convenient property for predicting ignition involving thermal inertia and ignition temperature.
Thermal runway: An accelerating chemical reaction due to an imbalance between heat loss and energy production.
Thermocouple: Device made of two dissimilar metal wires to measure temperature.
Thermodynamics: The study of energy and states of matter.
Thermophoresis: The process by which particles (soot) are transported due to a temperature difference.
Thermoplastic: A synthetic polymer that usually softens and melts on heating.
Thermosetting: Refers to a synthetic polymer that contains cross-link bonds and usually chars on heating.
Trifecta of fire growth: The combination of ignition, flame spread, and burning.

Turbulent: Refers to randomly fluctuating fluid motion around a mean flow.

Urban–wildland fire: A forest fire involving homes built in or around the forest.

Underventilated: Less than stoichiometric air is available.

Upper and lower flammability limits: Highest and lowest concentrations of fuel in air in which a premixed flame can propagate.

Vaporization temperature: The temperature of a vaporizing fuel while burning or needed to cause vaporization.

Ventilation factor: The parameter controlling air and smoke flow rate through a door or window, $A_o\sqrt{H_o}$.

Ventilation limited or ventilation controlled: State of a compartment fire where the air supply is limited, below stoichiometric; exiting smoke will have zero oxygen concentration; underventilated.

Viscous: Refers to fluid friction.

Vitiation: Refers to the reduction of oxygen concentration in air.

Volume fraction: Species concentration based on volume; or equivalently moles.

Vortex: A ring of eddies or swirling motion.

Wavelength: The distance traveled in one cycle or the speed of light divided by frequency.

Wind aided: Refers to air flow in the same direction as the fire spread.

Work: The movement of mass over a distance; mass times distance.

Yield: The mass of product produced per unit mass of fuel supplied.

Zone model: A type of computer fire model that approximates the fire conditions in a room as two uniform gas layers with a fire plume energy source.

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